INVESTIGATION OF RUDDER CHARACTERISTICS WITH VARIATION OF RUDDER POSITION IN A PROPELLER RACE

BY

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Cambridge, Massachusetts
May 19, 1950

Professor J. S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled, "Investigation of Rudder Characteristics with Variation of Rudder Position in a Propeller Race."

Respectfully,

Benjamin H. Downs
Lieutenant Commander
U. S. Navy

Charles B. Swayne
Lieutenant Commander
U. S. Navy

Richard E. Henning
Lieutenant
U. S. Navy

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Submitted in Partial Fulfillment of the

Requirements for the Degree of

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May 19, 1950

Signature of Thesis Supervisor

Signature of Chairman of Department Committee on Graduate Students

ACKNOWLEDGMENTS

We wish to express our appreciation to Mr. S. C. Gover of the David Taylor Model Basin for suggesting the subject matter of this investigation.

We are further indebted to Professor F. M. Lewis of the Department of Naval Architecture and Marine Engineering, M. I. T., for the use of the M. I. T. Propeller Tunnel and for his valuable advice in the determination and evaluation of the experimental data.

In addition we wish to thank Mr. Ray Johnson for his assistance and cooperation during the laboratory phase of the investigation.

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I. SUMMARY

This thesis was undertaken in order to investigate the effect on rudder force characteristics of variation of rudder position in a propeller race. It was thought that the results would contribute to the general fund of information about rudders since, to the knowledge of the authors, such an investigation had never before been carried out.

Utilizing the Massachusetts Institute of Technology propeller tunnel, the experimental data was obtained with a strain gauge type dynamometer which measured forces on a rudder in a propeller race. The rudder was mounted in the dynamometer which in turn was mounted in the tunnel in such a manner that the rudder could be moved transversely in small increments across the race of a right-hand propeller. At each such position, lift and drag readings were taken for rudder angles varying from 30° left to 30° right rudder in 5° increments. The speeds of both tunnel and propeller were maintained constant throughout all runs. In order to establish the average velocity of the race, a traverse was made using a pitot tube which gave only the component of velocity parallel to the tunnel axis. This necessitated the assumption that angle of attack was the same as rudder angle.

The results indicate that lift and drag vary widely depending upon the position of the rudder in the propeller race. A glance at Figures 18 and 19, which best summarize the results, indicates that the location of the rudder at either extreme of

the race appears to result in an appreciable loss of lift although this is accompanied by a reduced drag. The loss of lift would appear to make such a location undesirable for a warship.

With the rudder located between one sixth and one third of the propeller radius to the port side of the propeller centerline, very good lift characteristics were found, but again this was a region of high drag. On the basis of this experiment alone, using a single right-hand propeller, a single rudder, and constant speed, it appears that a narrow range may exist at about one sixth of the propeller radius to the starboard side of the propeller centerline where a high lift-drag ratio together with high lift occurs. It is believed that this cannot be stated conclusively until further intensive investigations are made, but the authors recommend that the region between one third of the radius to port and one third of the radius to starboard be thoroughly searched in small increments of transverse position using various combinations of rudders and propellers, and further that the tunnel and propeller be operated at various speeds. The use of a spherical or universal pitot tube would obviate the necessity for the assumption that angle of attack equals rudder angle.

The variations found in lift and drag with transverse rudder position,amounting to as much as 22%,point to an optimum rudder position, not necessarily on the propeller centerline, and it is strongly recommended that further investigations be made to determine and define such a location.

II. INTRODUCTION

The problems of turning and steering ships are as old as marine transportation itself, and in the present day of high speed surface and undersea warships are both vital and acute. From the time of the earliest truly scientific investigations to the present, extensive research and energy have been directed towards the development of the most effective and efficient means of maneuvering ships and towards methods of predicting reliably the performance of a particular design. Beyond this, effort has been expended in all maritime nations, towards isolating the effects of ship form, rudder shape, size, balance, and location on maneuverability and turning characteristics(1).

Essentially all investigations of rudders are concerned with lift, drag, normal force, tangential force, and torque on the rudder, and the reduction of these forces, where possible, to dimensionless coefficients of maximum utility. The investigation of the effect on rudder force characteristics, as measured by these coefficients, of varying the transverse position of a rudder in a propeller race was suggested by Mr. S. C. Gover of the David W. Taylor Model Basin. To the knowledge of the authors and after a survey of the literature, such an investigation has never been conducted. On the other hand, investigations of the optimum rudder location on a self-propelled model have been conducted. These concerned themselves primarily with optimum maneuverability of a particular hull form considering all elements, form, propeller location, and rudder location acting together(2).

It is therefore the intention of this thesis to investigate the effect on rudder force characteristics of varying the transverse position of a rudder in a propeller race, and thus to attempt to isolate one of the many variables affecting turning and steering characteristics of ships.

III. PROCEDURE

Initially it was apparent that in order to obtain the necessary data for this thesis, means must be found to measure flow velocities and propeller revolutions. These were required to define the characteristics of flow past the rudder with sufficient accuracy to evaluate the coefficients by which the performance of the rudder could be measured. Further it was necessary to develop a method of mounting a rudder in a propeller race in such a way that transverse position and rudder angle could be varied at will, and that at least two components of the force acting on the rudder could be determined.

The M. I. T. propeller tunnel, designed by Professor F. M. Lewis, appeared to be suited ideally to the measurement of flow and propeller revolutions with accurate control of each, and further afforded an excellent means of mounting the rudder and making observations(3). The rudder dynamometer developed by Rupp and Kissinger proved to be well adapted to transverse position variations as well as to the measurement of forces acting on the rudder for various rudder angles(4).

The normal direction of flow in the propeller tunnel is one in which the water flows in such a direction that the shafting and supporting struts are on the downstream side of the propeller. For the purpose of this investigation it was necessary to operate the tunnel with reverse flow in order that the shafting and struts would be on the upstream side of the propeller with the rudder in the propeller race. Since the nozzle,

diffuser, and straightening vanes of the tunnel were not designed for this direction of flow, the possibility existed that the flow might be unsatisfactory. While it is highly probable that flow conditions in this reverse direction were not as uniform as those of the designed flow direction it was believed that they would be sufficiently uniform to provide, at the least, good comparative data among the various transverse rudder positions. All phases of the investigation therefore were based upon this assumption. In operating the tunnel in reverse, however, the venturi meter by which water velocity is measured with the tunnel operating in the designed direction, was found to be located in a region of unstable flow. It became necessary, therefore, to install a pitot tube which could measure the average velocity of flow to the propeller. This pitot tube was placed about six inches forward and five inches outboard of the propeller tip and was left in place throughout all runs.

The rudder dynamometer employs SR-4 strain gauges to give a measure of lift, drag and torque on the rudder[4]. The dynamometer was regauged immediately prior to its use and all strain gauges were tested prior to assembly of the dynamometer components. Certain minor modifications were made to improve its characteristics and to alleviate difficulties experienced in calibration. The dynamometer was bolted to Z-bars fitted at the top of the tunnel test section as shown in Plate I. The upper flange of these Z-bars had holes drilled on one-inch centers so that a complete traverse of the propeller race could be made in one-inch increments.

Before and after tests, the dynamometer was calibrated by mounting it in a wooden test stand and applying known horizontal loads in the transverse and longitudinal directions to a test stock inserted in the dynamometer. This was accomplished by reeving a wire from the test stock, over a pulley to a weight pan and placing known weights on the pan. Strain readings for each longitudinal and transverse load thus applied were read on a Baldwin-Southwark strain indicator which was connected through a switching box to the strain gauges on the dynamometer. The calibration curves obtained from these readings showing strain readings versus applied force are shown in Figures 1, 2 and 23. When taking data during tests the reverse procedure was used; that is strain readings were taken for longitudinal and transverse force and these were converted through the use of the calibration curves into lift and drag.

In arriving at the flow velocity to be used during the tests the force acting upon the rudder was taken to be a function of several variables:

$$F = f(\rho, V, \mu, L, c, g, \alpha, r_1, r_2, --)$$

where ρ = mass density of water

V = Average axial velocity of the propeller race in way of the rudder in ft./sec.

μ = viscosity of the fluid

L = a characteristic length of the body

c = speed of sound in water

g = acceleration of gravity

α = angle of attack

r_1, r_2--- form factors

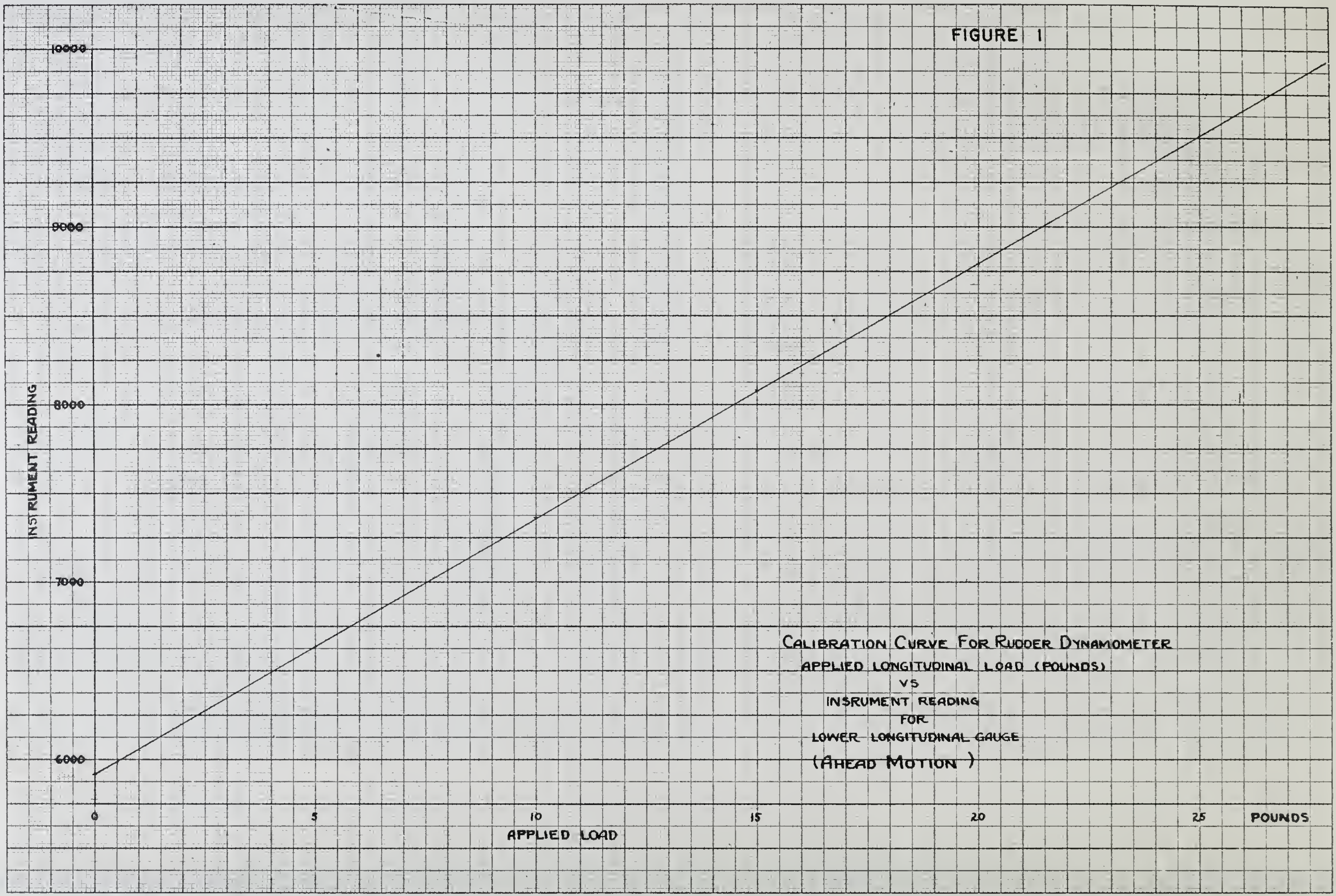
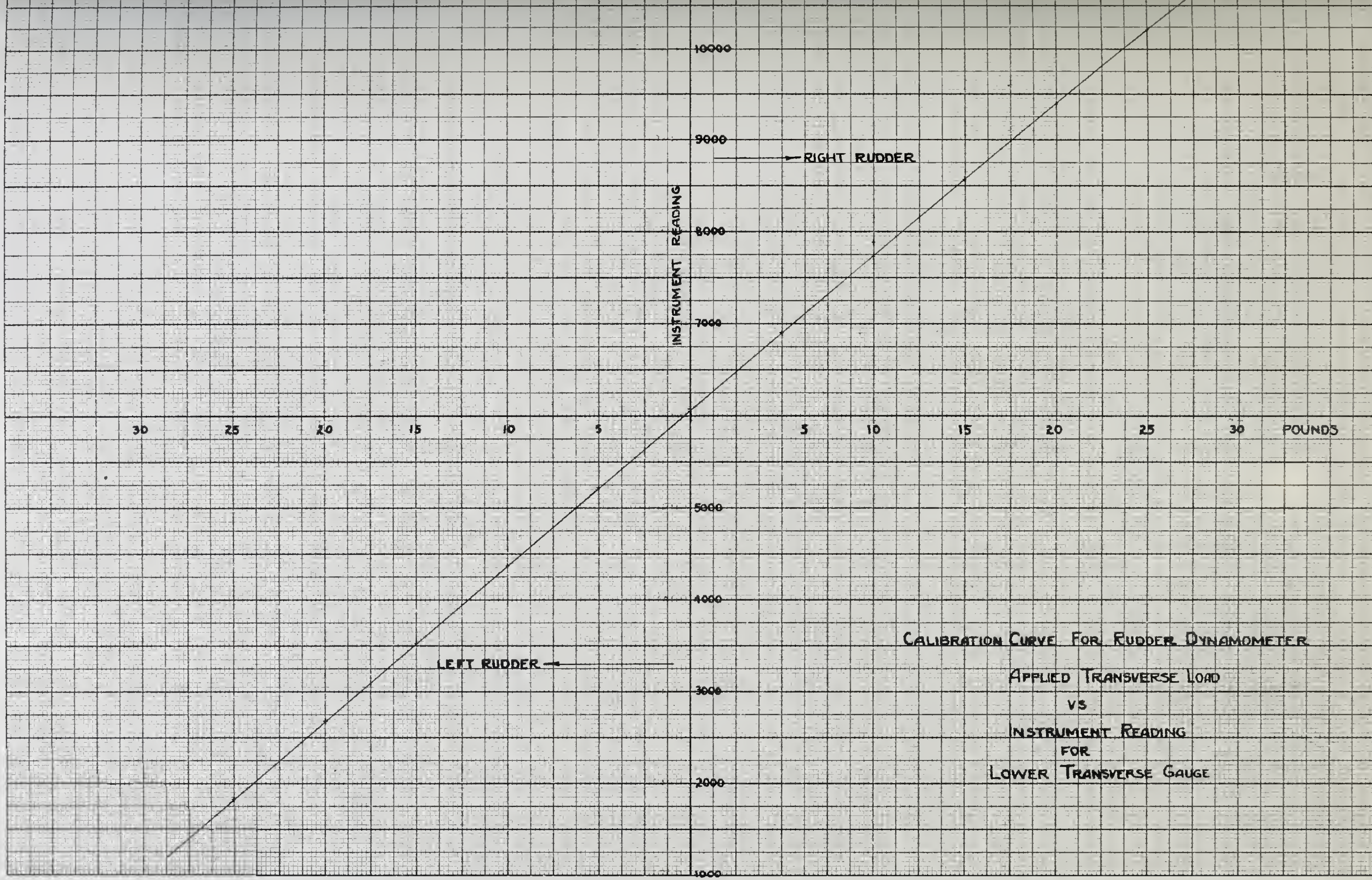


FIGURE 1
CALIBRATION CURVE FOR RUDDER DYNAMOMETER
APPLIED LONGITUDINAL LOAD (POUNDS)
VS
INSRUMENT READING
FOR
LOWER LONGITUDINAL GAUGE
(AHEAD MOTION)
INSTRUMENT READING
10000
9000
8000
7000
6000
0
5
10
15
20
25
POUNDS
APPLIED LOAD

FIGURE 2



10000
9000
RIGHT RUDDER
INSTRUMENT READING
8000
7000
30
25
20
15
10
5
5
10
15
20
25
30
POUNDS
5000
4000
LEFT RUDDER
3000
2000
1000
CALIBRATION CURVE FOR RUDDER DYNAMOMETER
APPLIED TRANSVERSE LOAD
VS
INSTRUMENT READING
FOR
LOWER TRANSVERSE GAUGE

Since the rudder can be assumed to be expanded geometrically to full size for ship use, the form factors r_1, r_2, --- are taken as constant. Hence, by dimensional analysis it can be shown that:

$$F = \frac{1}{2} \quad V^2L^2f(\alpha, \frac{V}{C}, \frac{gL}{V^2}, \frac{VL}{\nu})$$

where $\nu = \frac{\mu}{\rho}$

The term $\frac{V}{c}$, commonly known as the Mach Number, can be considered to have negligible effect since it is of importance only where it approaches or exceeds one, in which case shock effects may be of consequence. Since V is very small in comparison with c, no shock effects are to be expected.

The quantity $\frac{VL}{\nu}$, known as the Reynolds Number, should be kept constant in predicting full-scale performance from model tests. It was not possible to operate at the same Reynolds Number in the tunnel as would be encountered in full-scale operation, but this was not considered serious since flow in the tunnel is turbulent at low water velocities. In the turbulent range of flow the effect of the Reynolds Number decreases as the Reynolds Number increases, approaching zero asymptotically. It has been shown in previous model tests in the M. I. T. Propeller Tunnel that the effective Reynolds Number is in that portion of the turbulent range where its influence may be disregarded(4).

The Froude Number $\frac{gL}{V^2}$ is of importance only where surface effects are encountered, and it has been shown in the past that geometrically similar ships operating at the same Froude Number will generate geometrically similar surface waves. The deep submergence of the rudder during these tests was thought to be sufficient to eliminate surface effects entirely. Nevertheless the ship on which such a full-scale rudder would normally be mounted would be subject to this limitation and for this reason it was considered appropriate to operate the tests at such a velocity that the Froude Number would be that of a typical destroyer rudder with the ship operating at maximum speed. The speed thus selected resulted in a flow velocity which fell within the favorable operating range of the tunnel and dynamometer.

When the foregoing analysis is employed for the case of a rudder in a free stream, α is usually taken as the rudder angle. While it was recognized that this use of α might not be rigorously correct for a rudder behind a propeller with the flow unevenly distributed by the propeller, an exact determination of angle of attack was beyond the limits of the equipment available. For this reason α, the angle of attack, was assumed to be identical with rudder angle.

The rudder force can be expressed then as

$$F = \frac{1}{2}\rho V^2 A f(\alpha)$$

and if by definition

$$C_F = f(\alpha)$$

then

$$F = C_F \frac{1}{2} \rho V^2 A$$

This force can be resolved into lift and drag components

whence $$L = C_L \cdot \frac{1}{2} \rho V^2 A$$

$$D = C_D \cdot \frac{1}{2} \rho V^2 A$$

and transforming

$$C_L = \frac{L}{\frac{1}{2} \rho A V^2}$$

$$C_D = \frac{D}{\frac{1}{2} \rho A V^2}$$

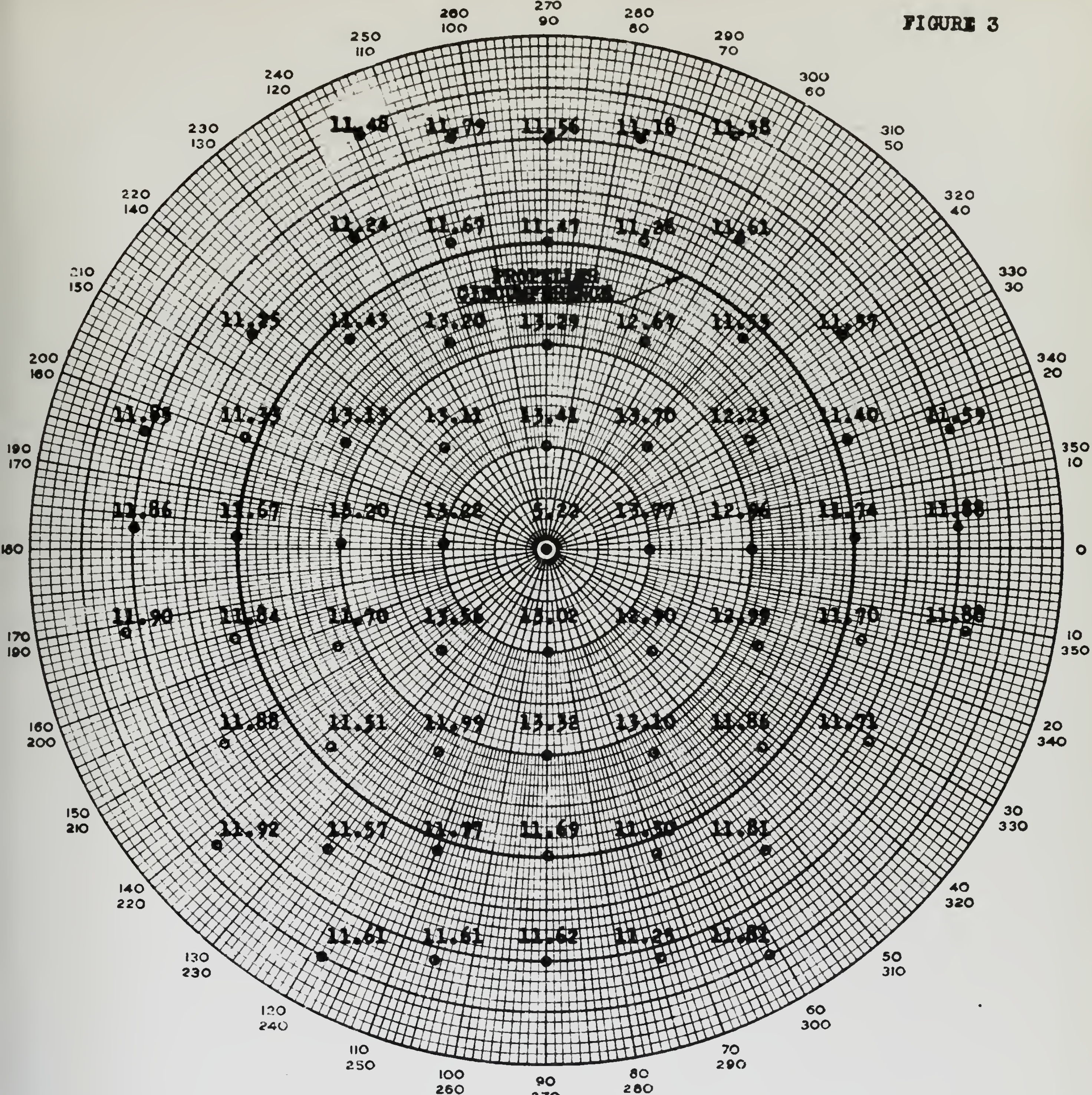
This is the form in which the results are presented. A sample calculation is shown in the Appendix.

The rudder used had an aspect ratio of one with an area of 12.03 square inches, a thickness ratio of 0.187 and 30% balance.

A conventional four-blade right-hand propeller with a six-inch diameter and a constant pitch ratio of one was used. It was operated at such a speed as to give a slip representative of that for full-scale operation under the stated assumption that reasonable flow characteristics at the propeller would be realized. In order to ascertain this flow and to get an average flow velocity at the rudder, a complete pitot traverse was made across the propeller race. The results of this traverse are shown in Figure 3.

In taking experimental data, the dynamometer was located at a specific transverse position and readings were taken for rudder angles varying from 30° left to 30° right rudder in

FIGURE 3



PLOT OF VELOCITIES (ft./sec.) ACROSS PROPELLER RACE

Tunnel Velocity = 11.22 ft./sec.
Propeller Speed = 1500 RPM

5^0 increments. This procedure was repeated for each of the transverse rudder positions. Propeller and tunnel speeds were maintained constant throughout the procedure.

Plates II through V show the rudder located at two different transverse positions for each of which two rudder angles are shown. Tunnel speed at the time of the photographs was 11.22 feet per second and propeller speed was 1500 R.P.M.

IV. RESULTS

Results are shown entirely in graphical form in Figures 4 to 22.

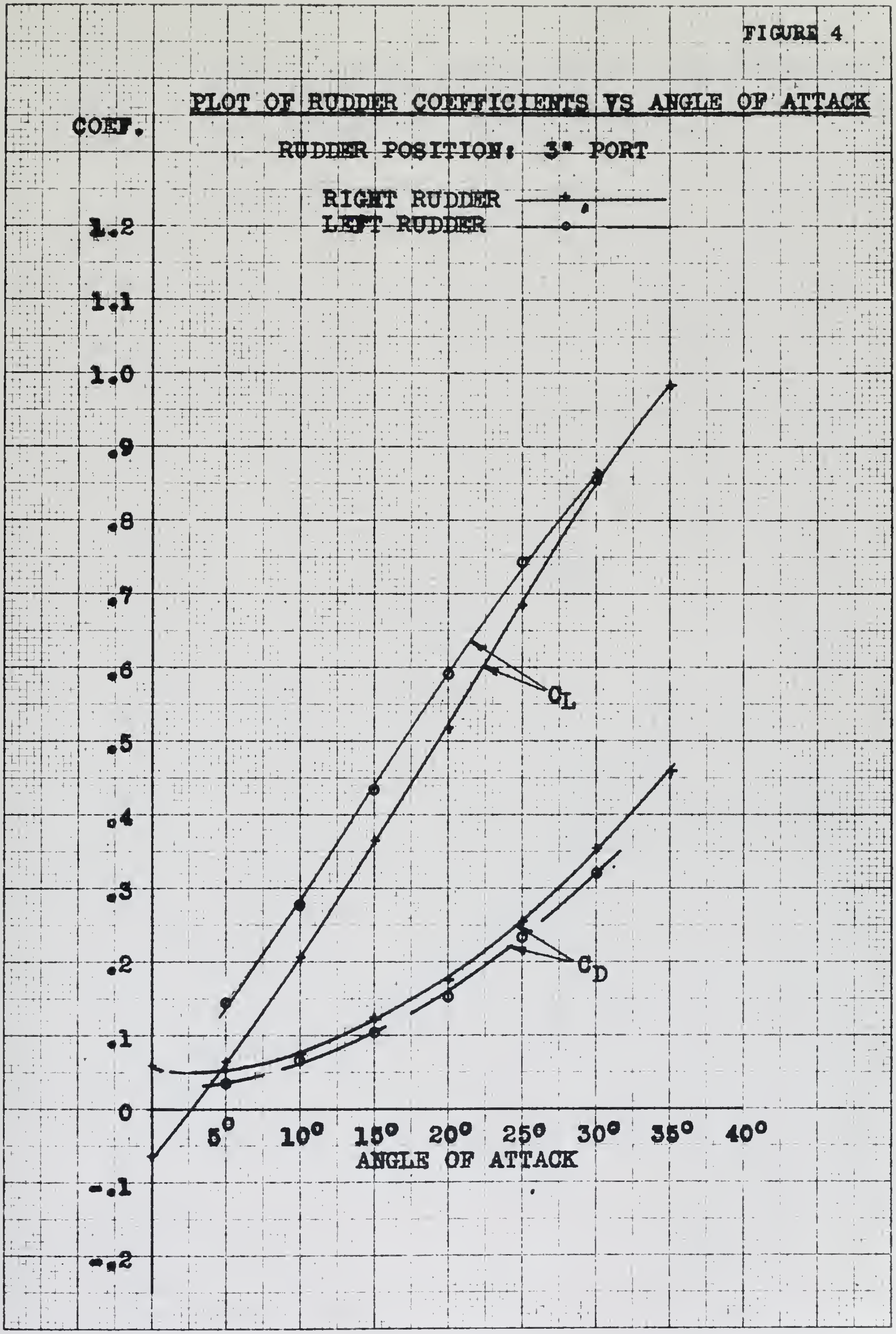


FIGURE 4
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
COEF.
RUDDER POSITION: 3° PORT
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_L
C_D
5°
10°
15°
20°
25°
30°
35°
40°
ANGLE OF ATTACK

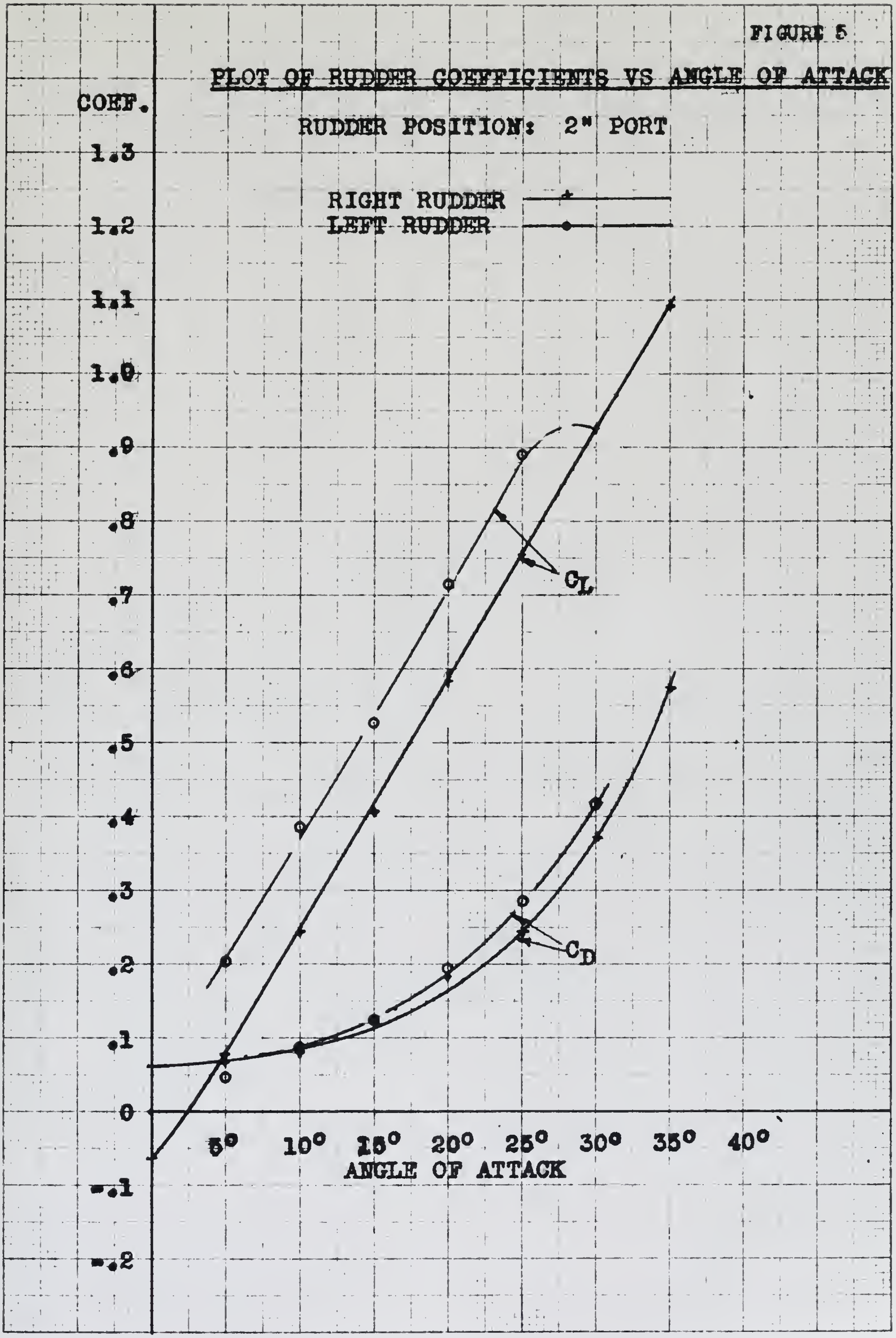


FIGURE 5
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 2" PORT
RIGHT RUDDER
LEFT RUDDER
COEF.
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_L
C_D
5°
10°
15°
20°
25°
30°
35°
40°
ANGLE OF ATTACK

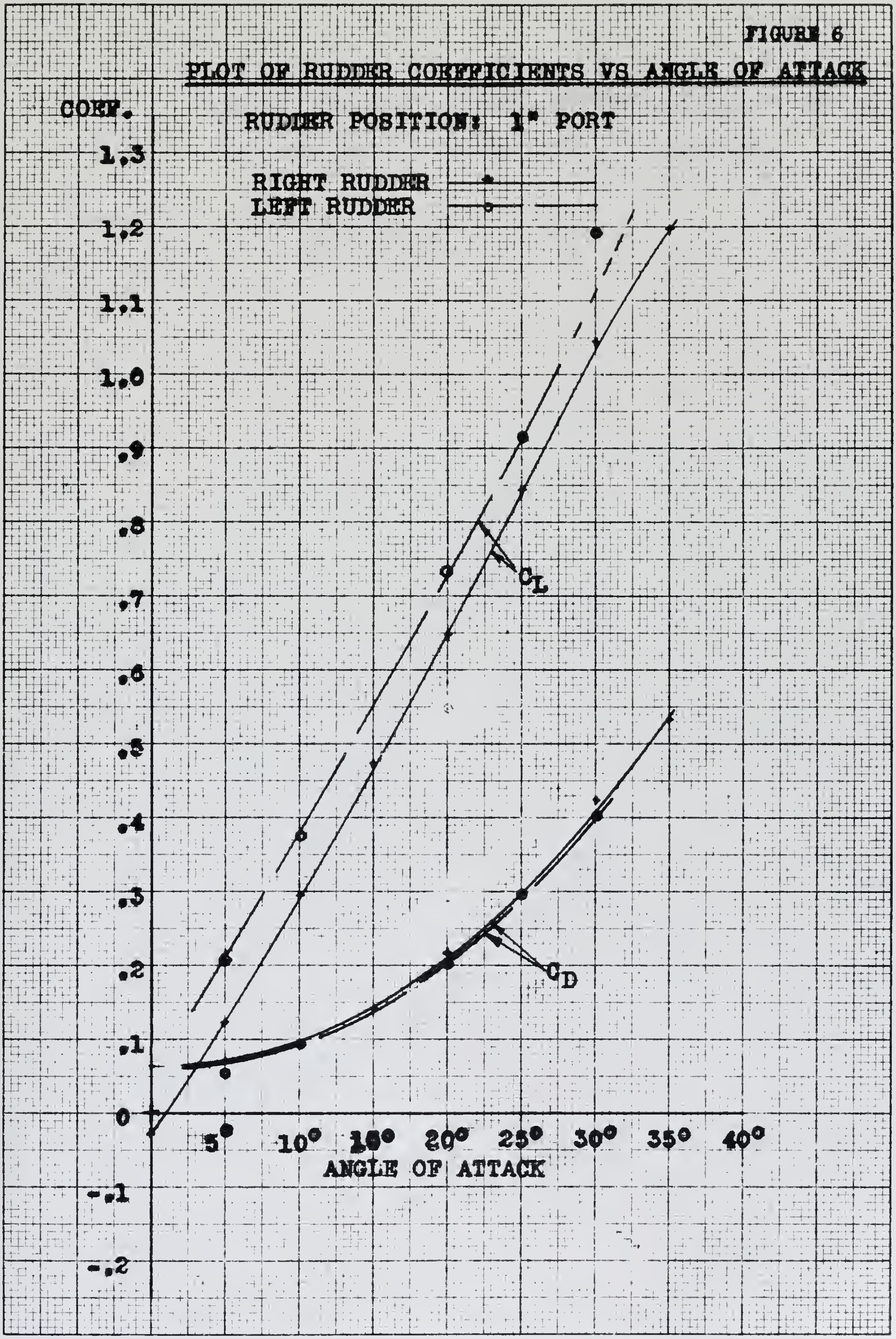
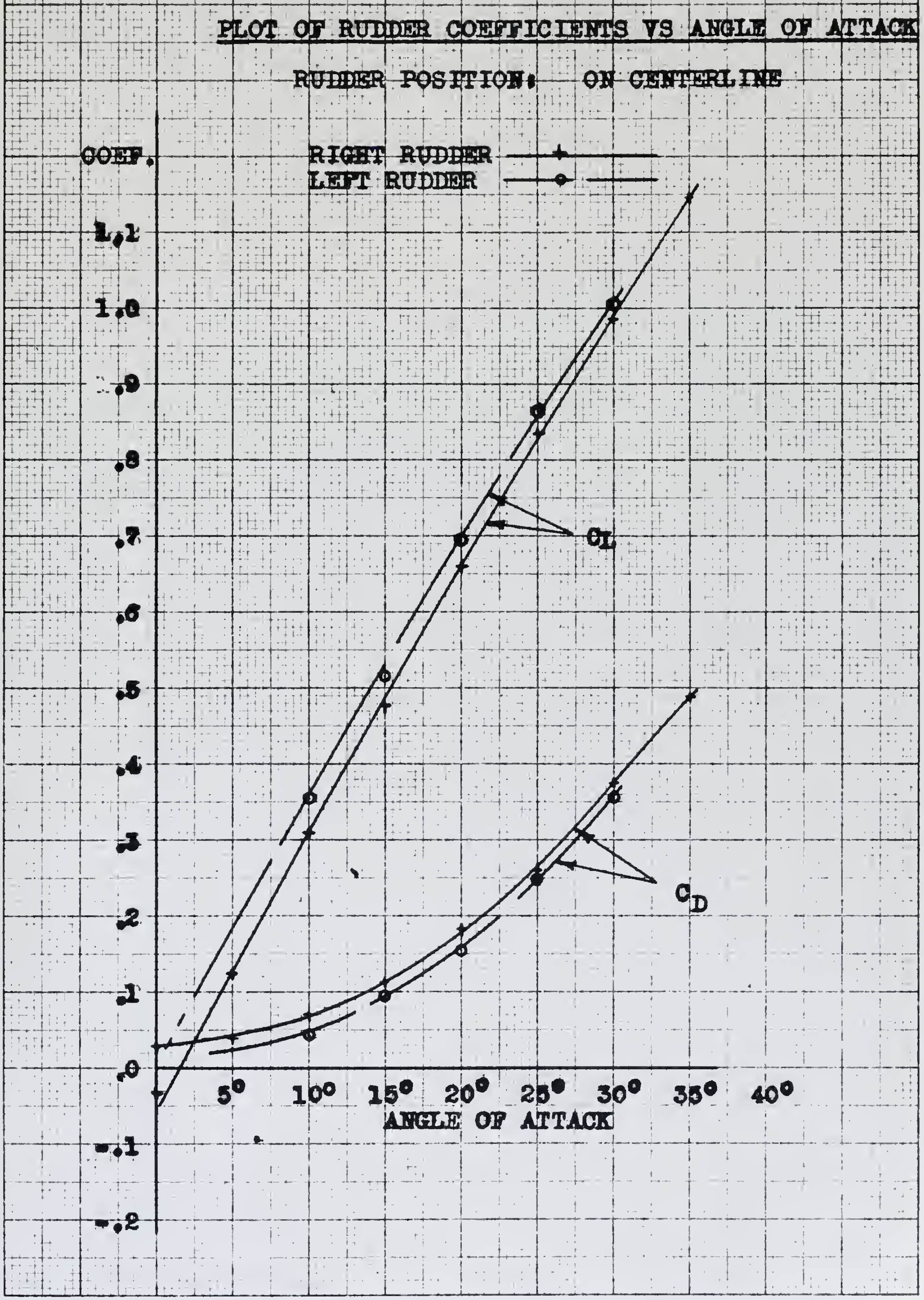


FIGURE 6
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
COEF.
RUDDER POSITION: 1" PORT
RIGHT RUDDER
LEFT RUDDER
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_L
C_D
5°
10°
15°
20°
25°
30°
35°
40°
ANGLE OF ATTACK

FIGURE 7


PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: ON CENTERLINE
COEF.
RIGHT RUDDER
LEFT RUDDER
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
-.1
-.2
C_L
C_D
5°
10°
15°
20°
25°
30°
35°
40°
ANGLE OF ATTACK

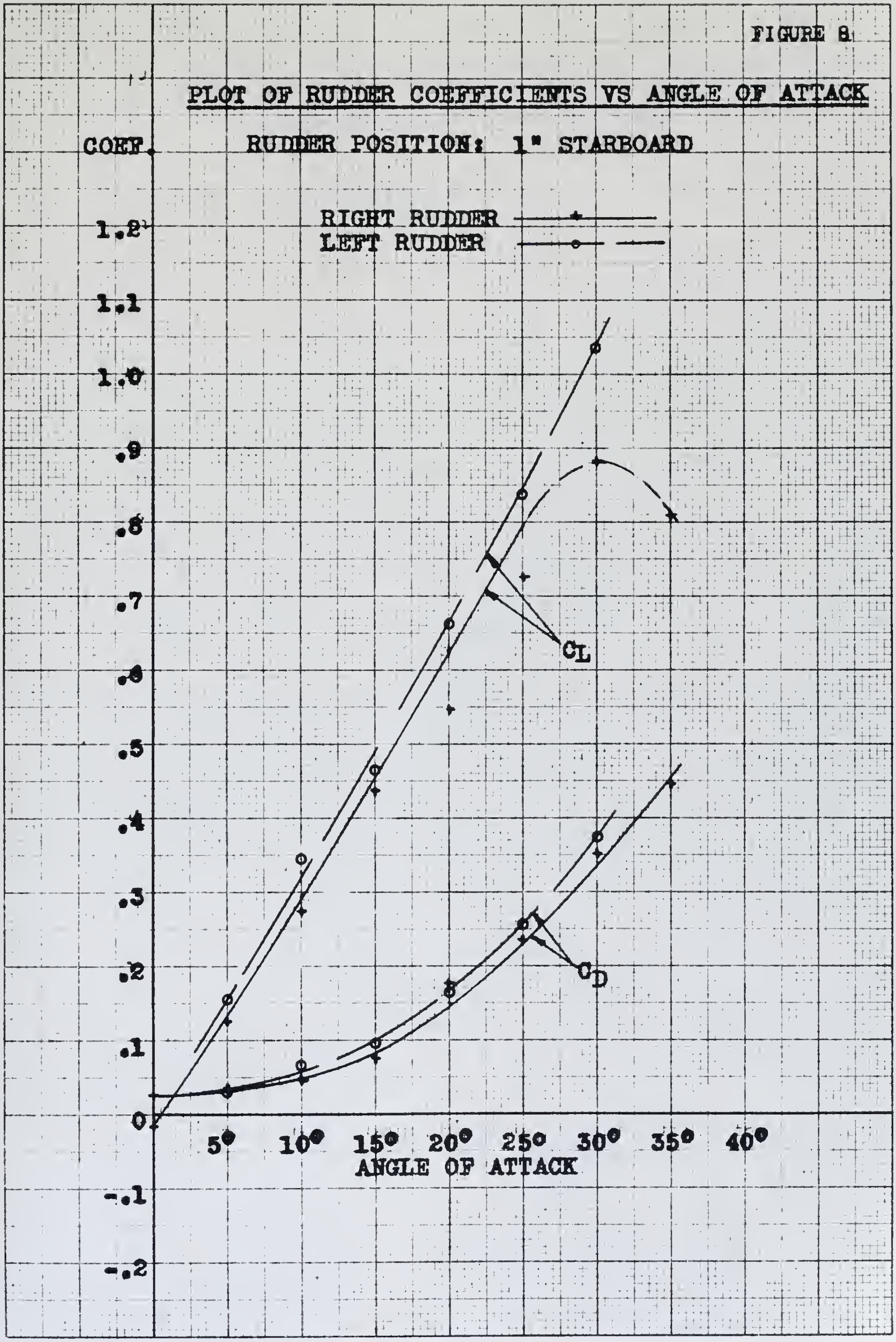


FIGURE 8
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
COEF.
RUDDER POSITION: 1" STARBOARD
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_L
C_D
5°
10°
15°
20°
25°
30°
35°
40°
ANGLE OF ATTACK

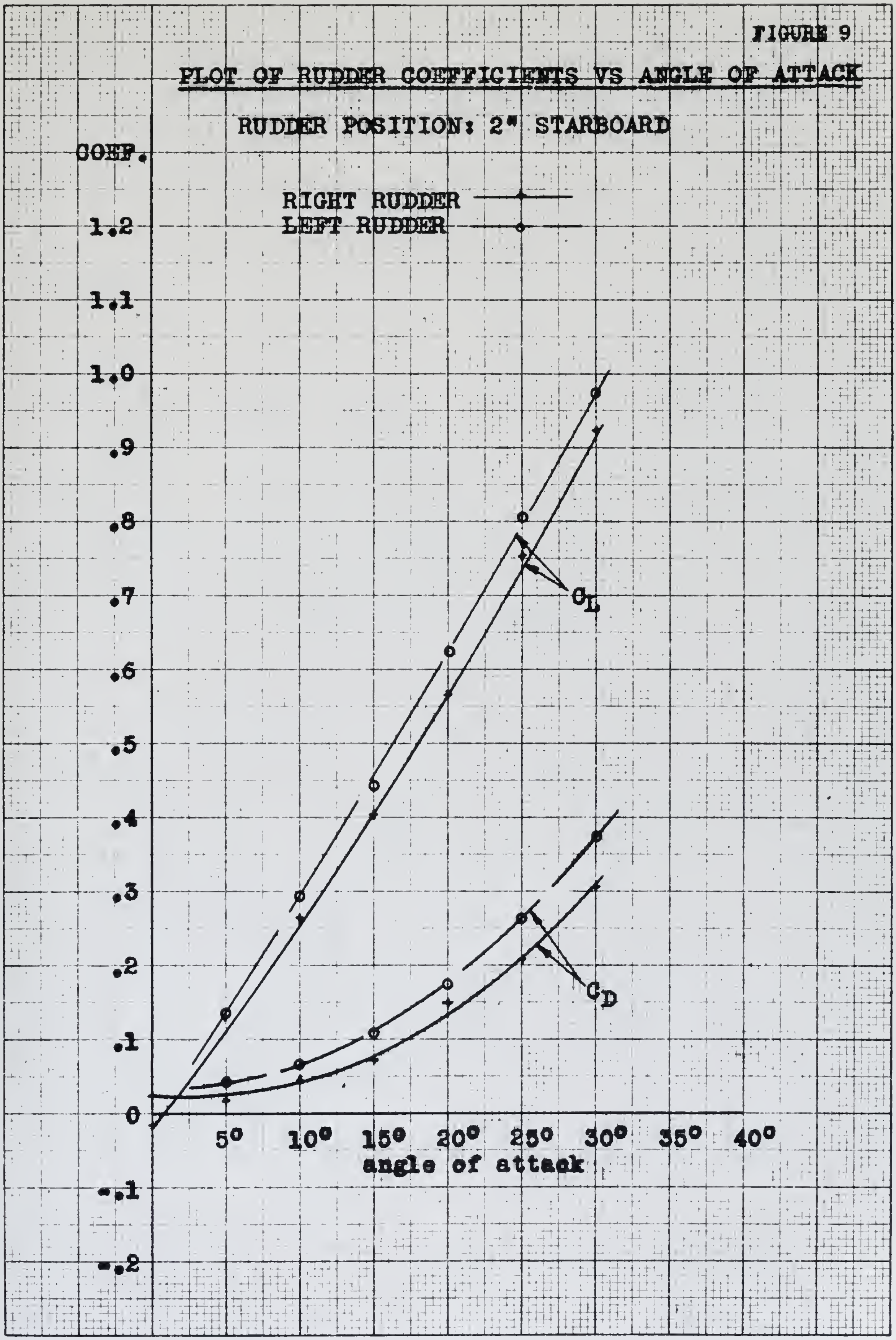


FIGURE 9
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 2" STARBOARD
COEF.
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_L
C_D
5°
10°
15°
20°
25°
30°
35°
40°
angle of attack

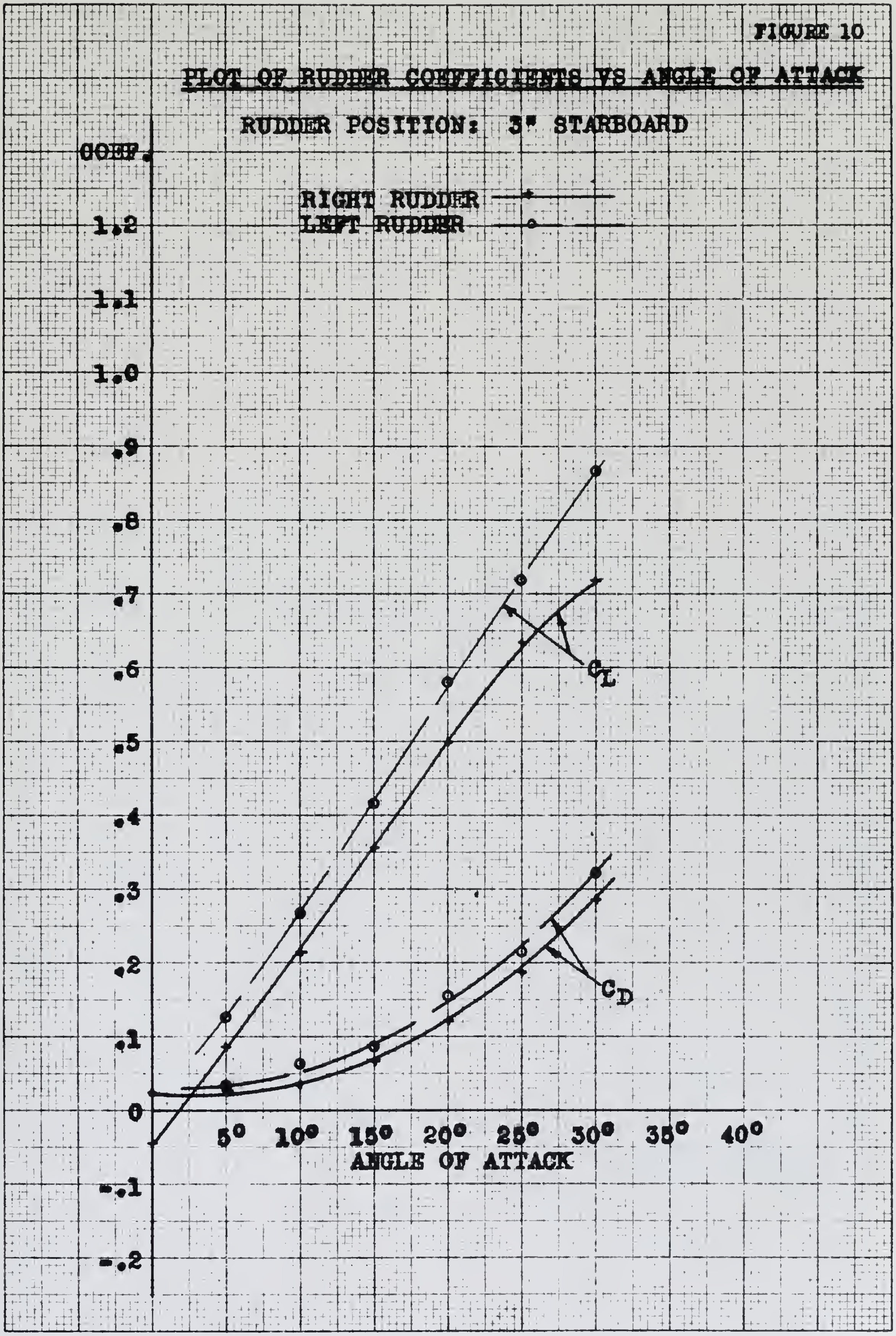


FIGURE 10
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 3" STARBOARD
COEFF.
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_L
C_D
5°
10°
15°
20°
25°
30°
35°
40°
ANGLE OF ATTACK

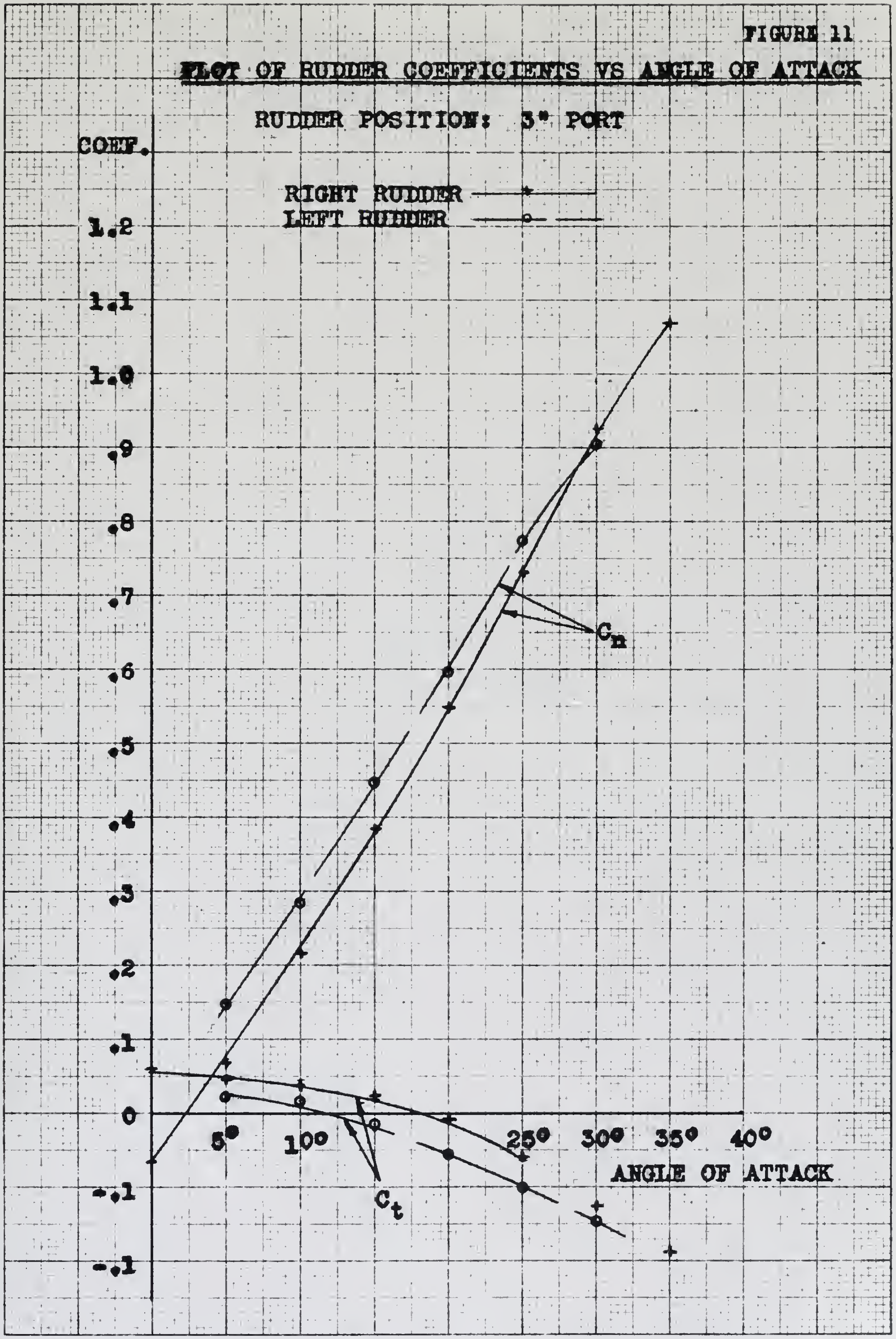


FIGURE 11
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 3° PORT
COEF.
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.1
5°
10°
25°
30°
35°
40°
ANGLE OF ATTACK
C_n
C_t

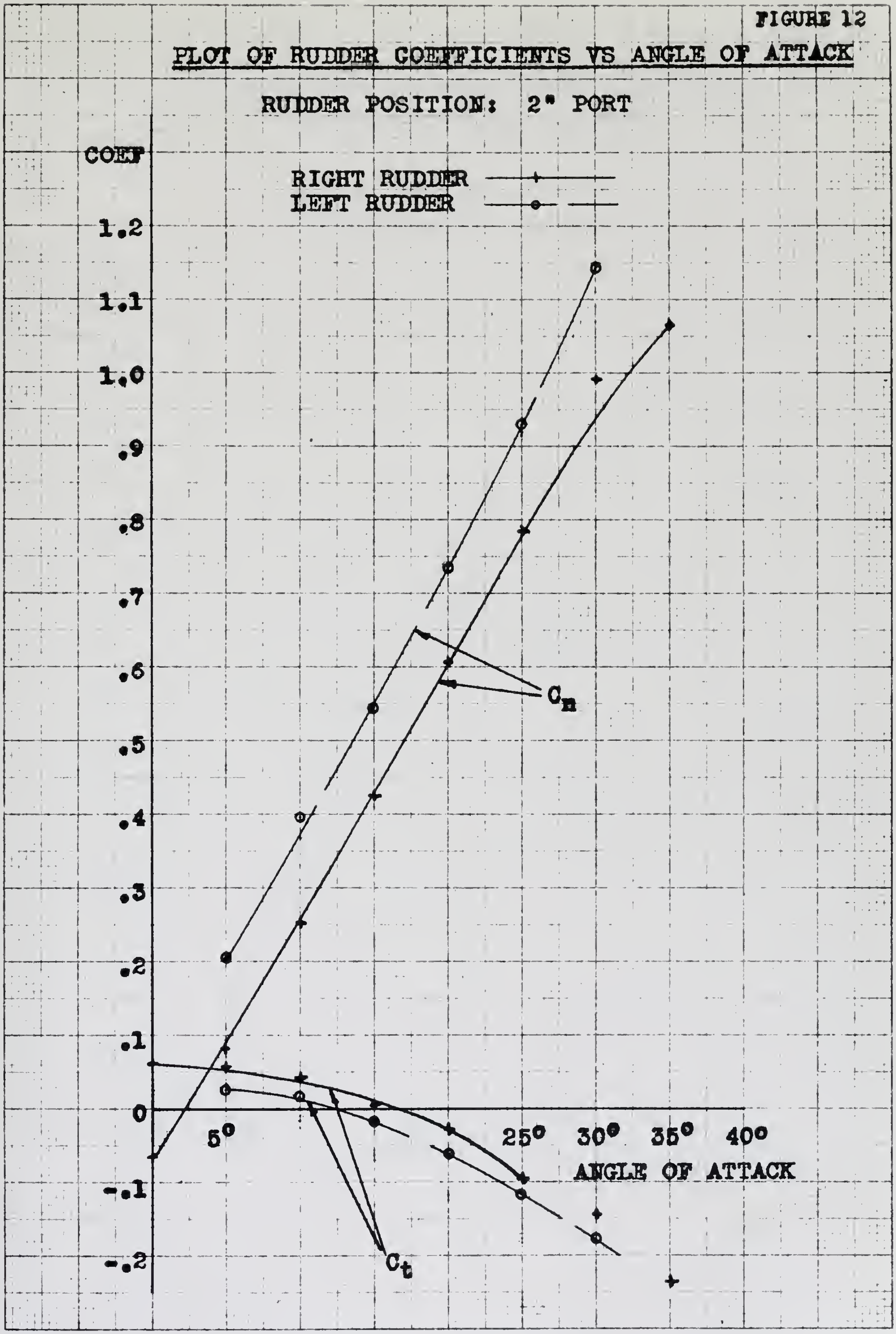


FIGURE 12
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 2" PORT
COEF
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_n
C_t
5°
25°
30°
35°
40°
ANGLE OF ATTACK

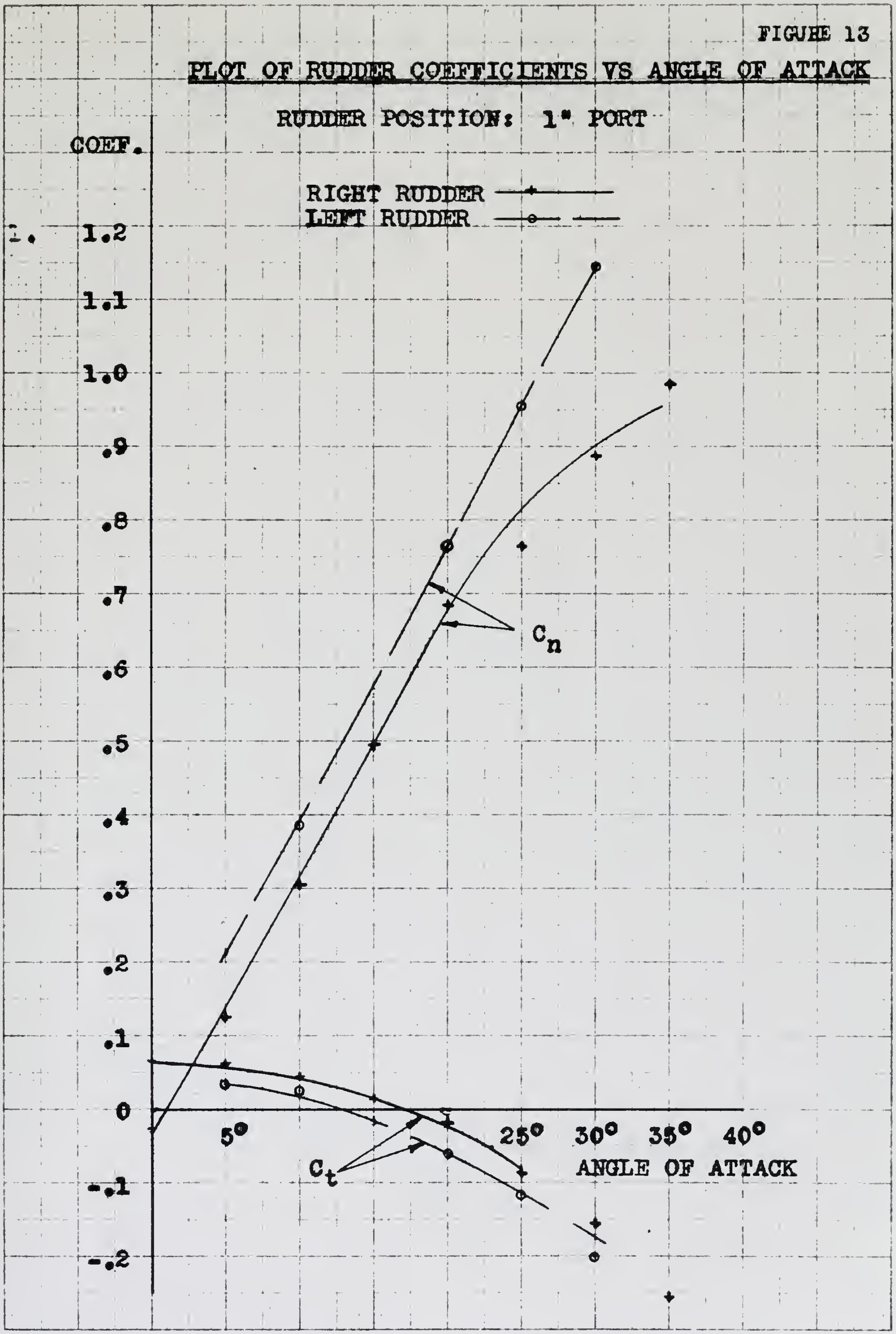


FIGURE 13
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 1° PORT
COEF.
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_n
C_t
5°
25°
30°
35°
40°
ANGLE OF ATTACK

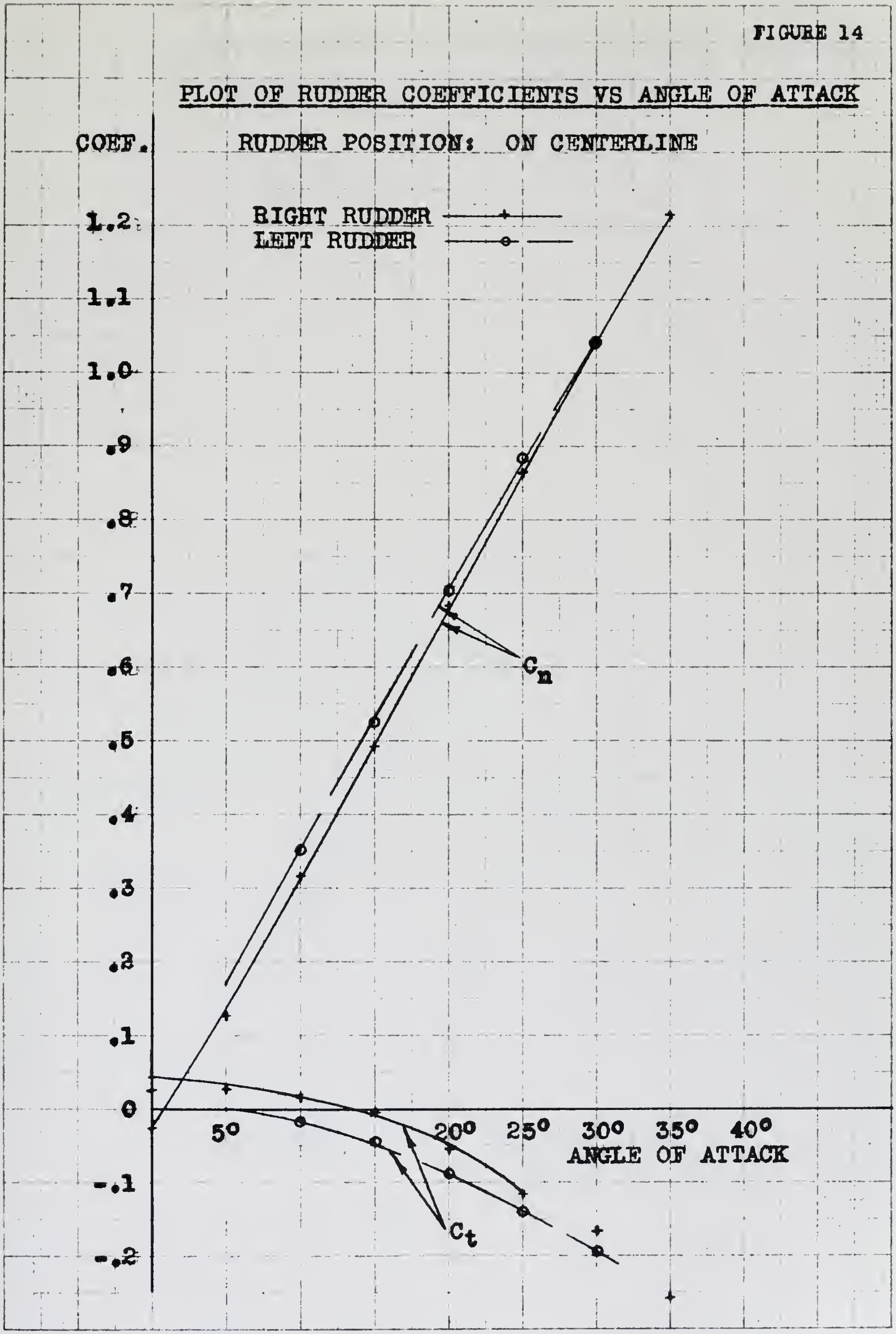


FIGURE 14
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
COEF.
RUDDER POSITION: ON CENTERLINE
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_n
C_t
5°
20°
25°
30°
35°
40°
ANGLE OF ATTACK

FIGURE 15

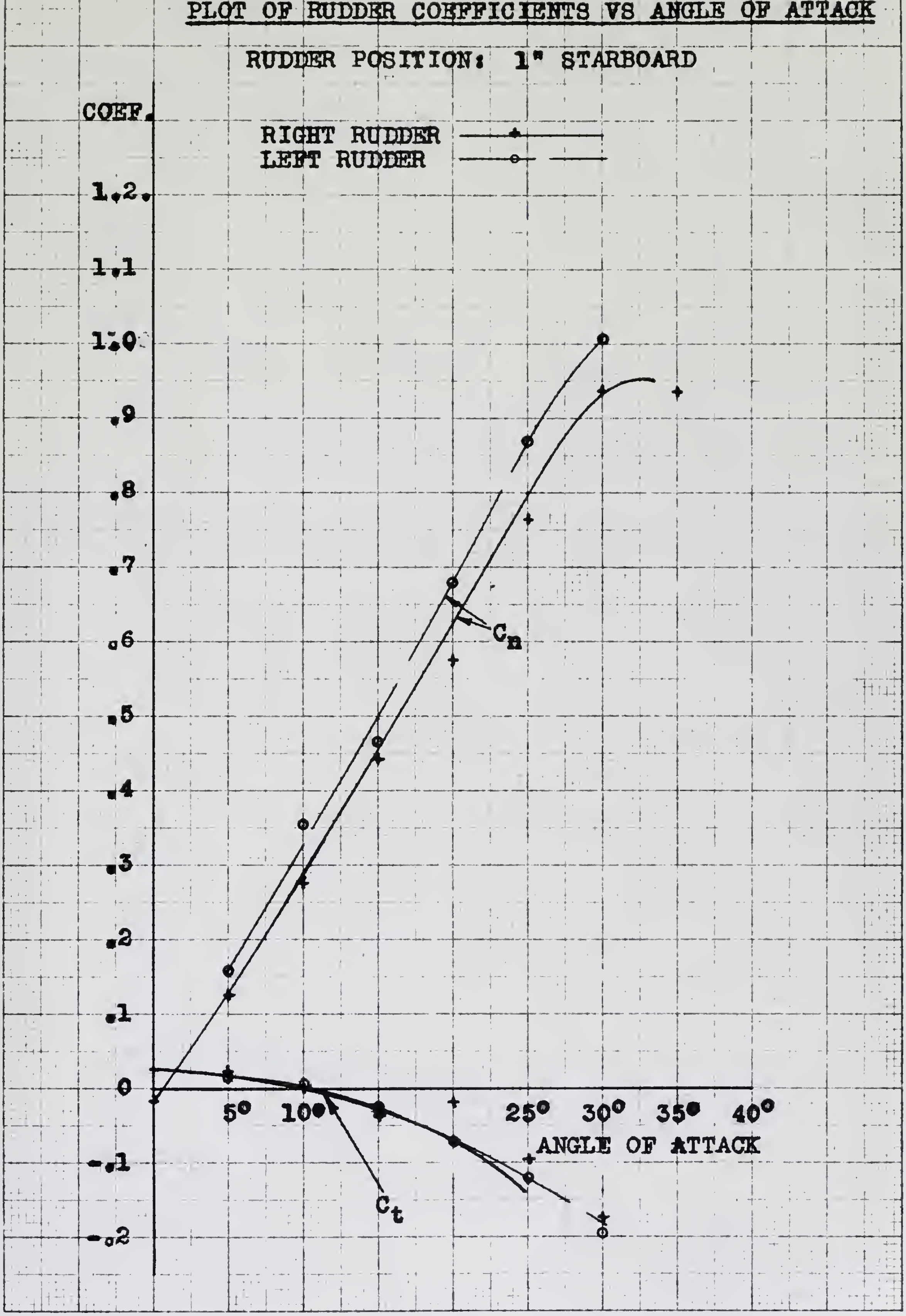
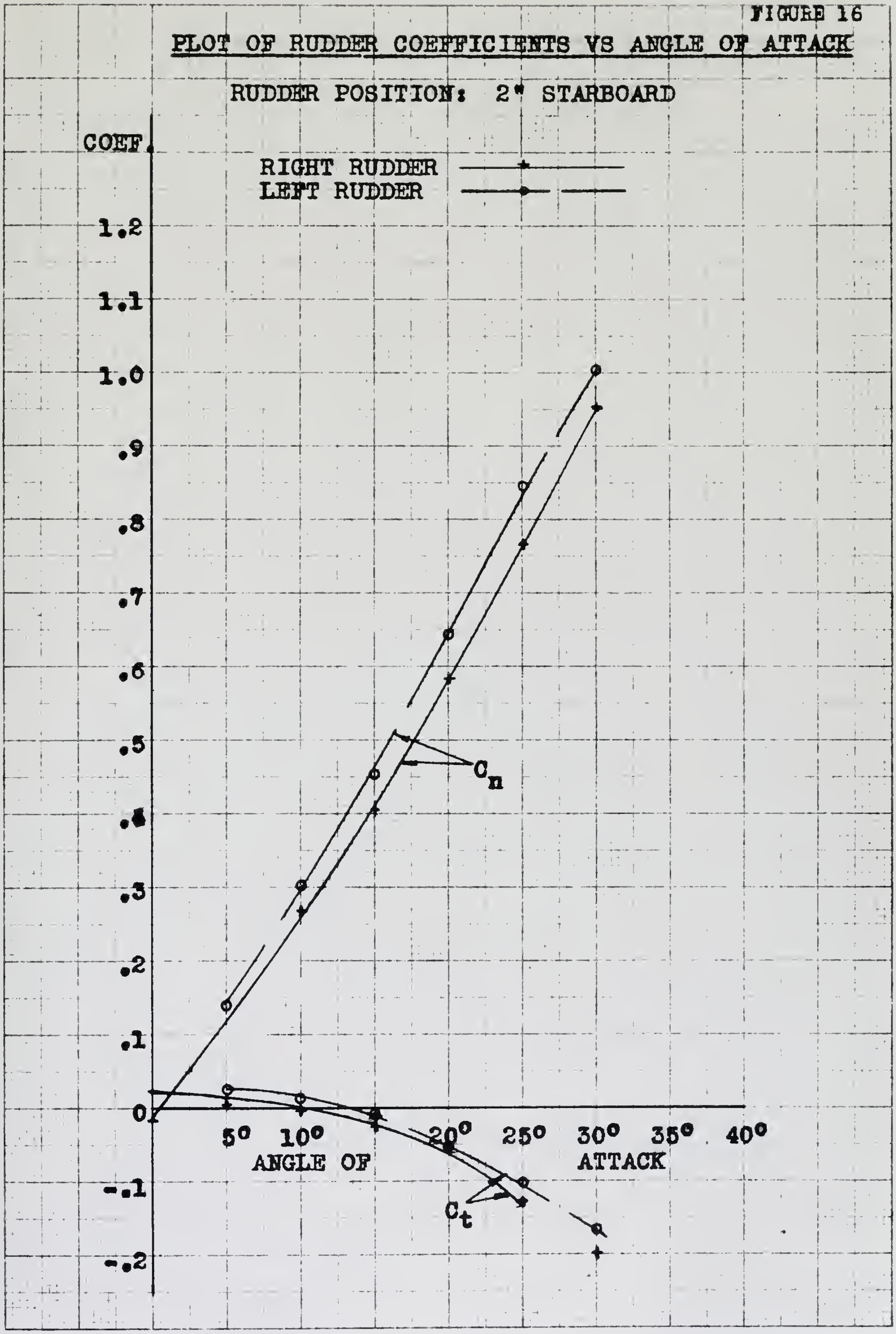

PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 1° STARBOARD
COEF.
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
5°
10°
25°
30°
35°
40°
ANGLE OF ATTACK
C_n
C_t

FIGURE 16


PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 2° STARBOARD
COEF.
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
C_n
C_t
5° 10°
20° 25°
30° 35° 40°
ANGLE OF
ATTACK

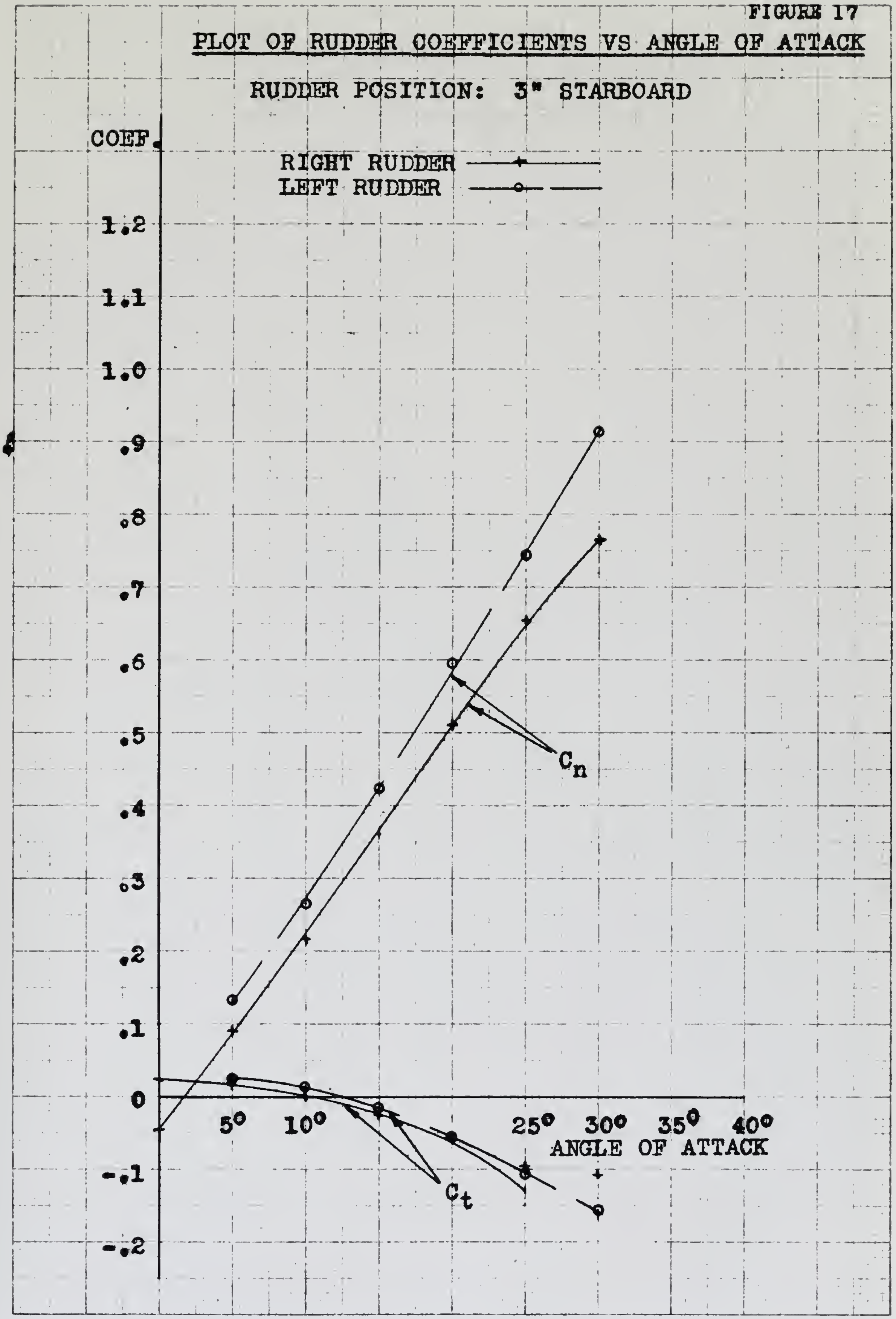
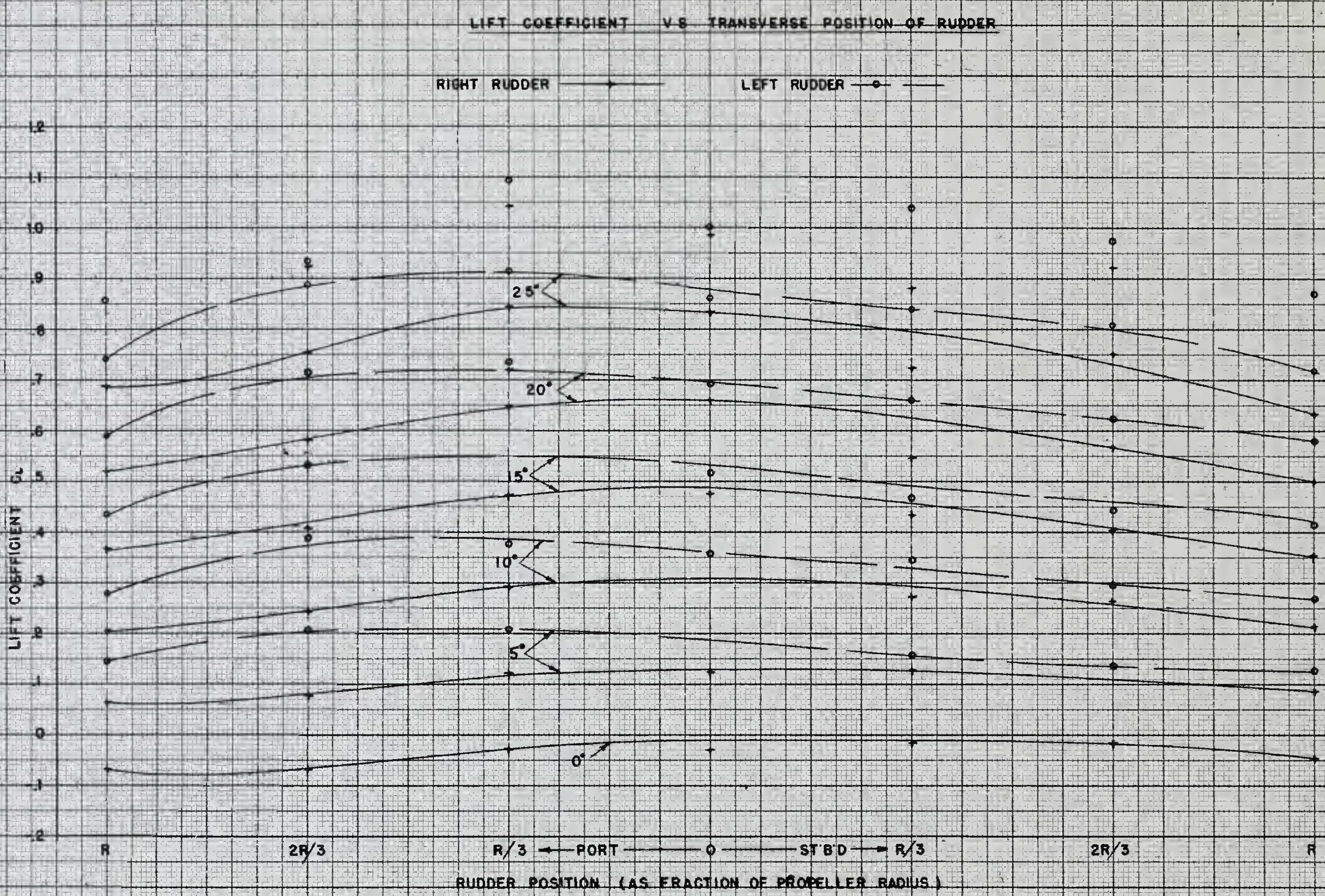


FIGURE 17
PLOT OF RUDDER COEFFICIENTS VS ANGLE OF ATTACK
RUDDER POSITION: 3° STARBOARD
COEF.
RIGHT RUDDER
LEFT RUDDER
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
5°
10°
25°
30°
35°
40°
ANGLE OF ATTACK
C_n
C_t

FIGURE 18



LIFT COEFFICIENT VS TRANSVERSE POSITION OF RUDDER
RIGHT RUDDER
LEFT RUDDER
LIFT COEFFICIENT C_L
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
25°
20°
15°
10°
5°
0°
R
2R/3
R/3 ← PORT — 0 — ST'B'D → R/3
2R/3
R
RUDDER POSITION (AS FRACTION OF PROPELLER RADIUS)

FIGURE 19

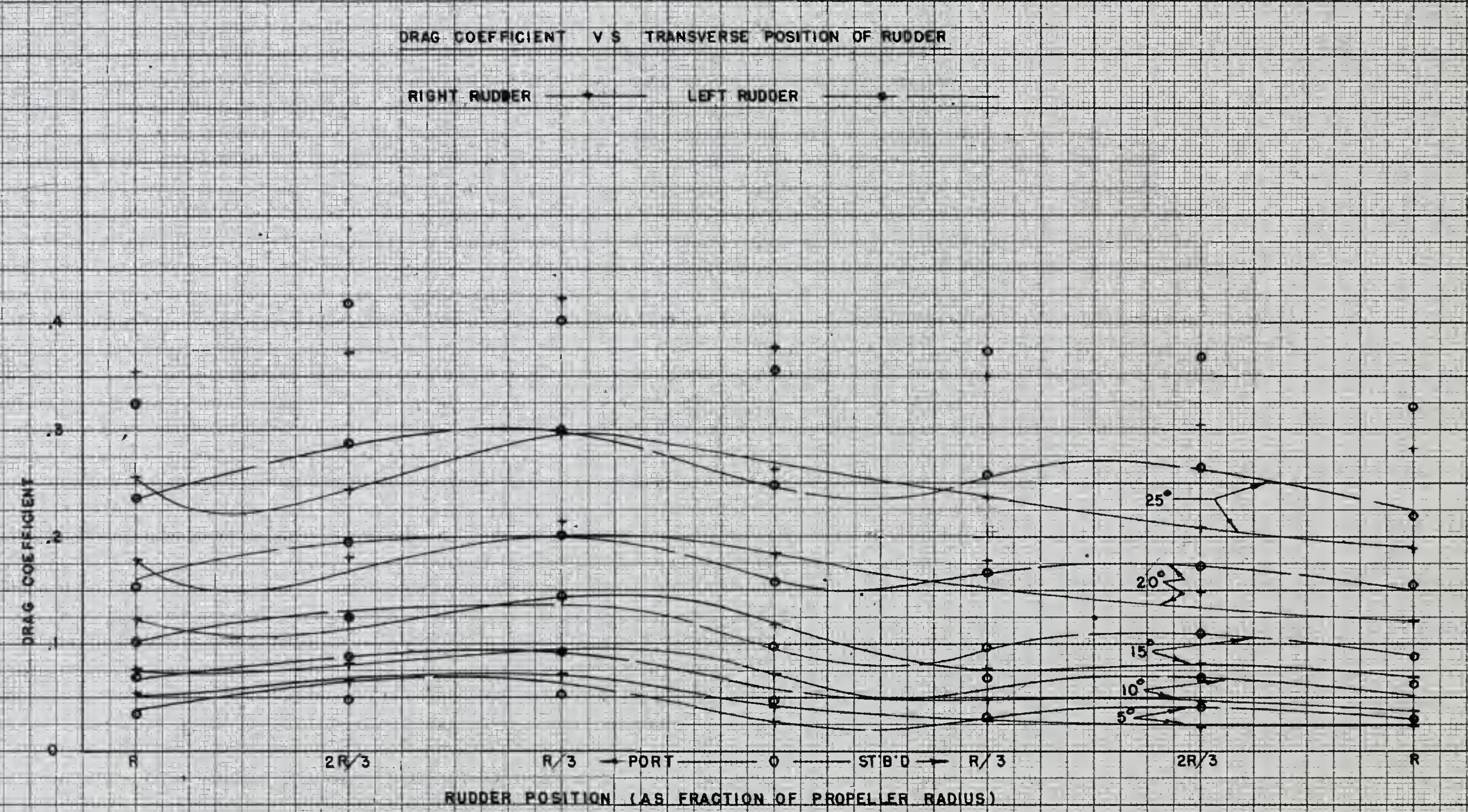

DRAG COEFFICIENT VS TRANSVERSE POSITION OF RUDDER
RIGHT RUDDER
LEFT RUDDER
DRAG COEFFICIENT
.4
.3
.2
.1
0
25°
20°
15°
10°
5°
R
2R/3
R/3
PORT
0
ST'B'D
R/3
2R/3
R
RUDDER POSITION (AS FRACTION OF PROPELLER RADIUS)

FIGURE 20

TANGENTIAL FORCE COEFFICIENT (RIGHT RUDDER) VS TRANSVERSE POSITION OF RUDDER

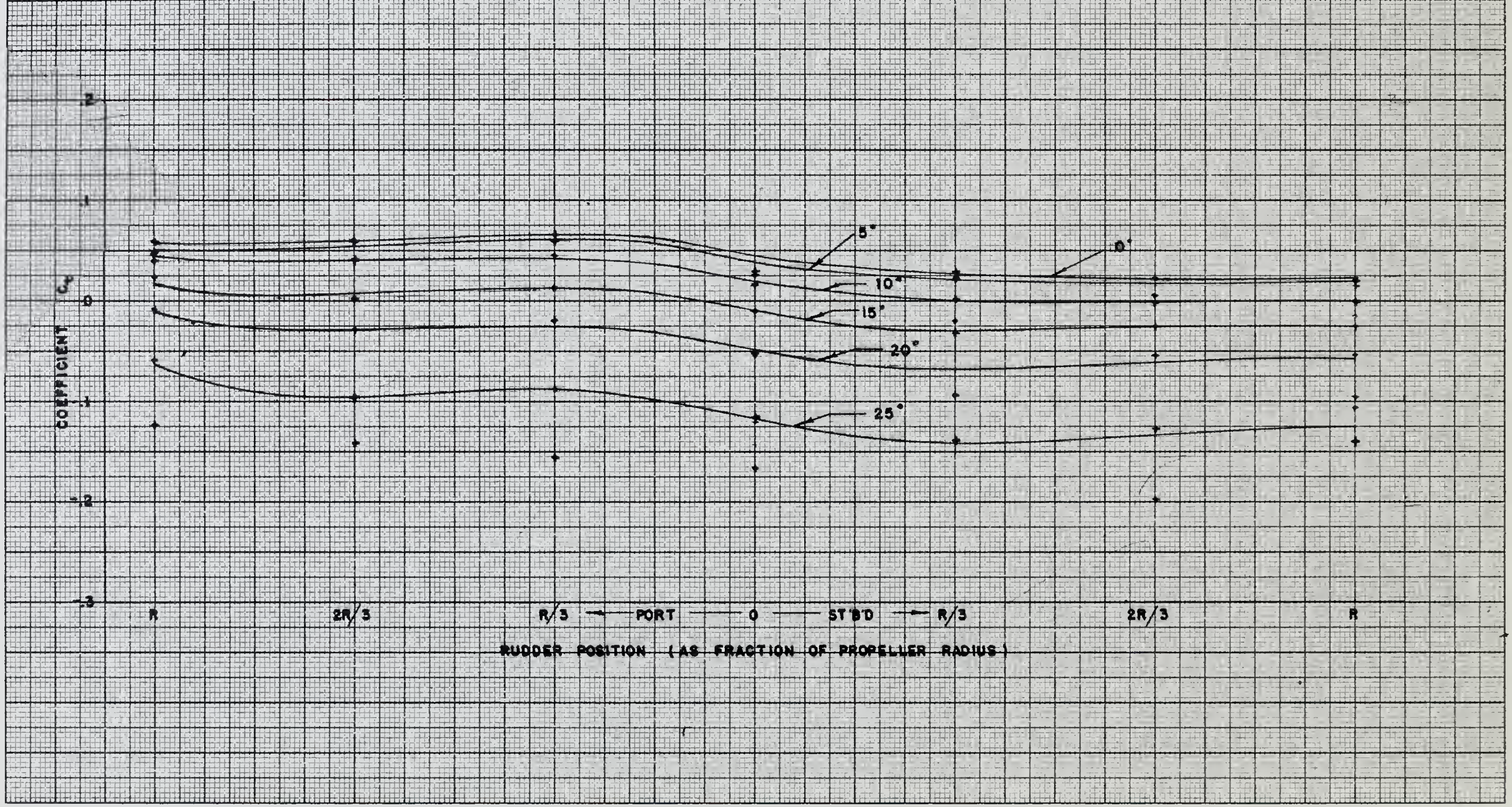
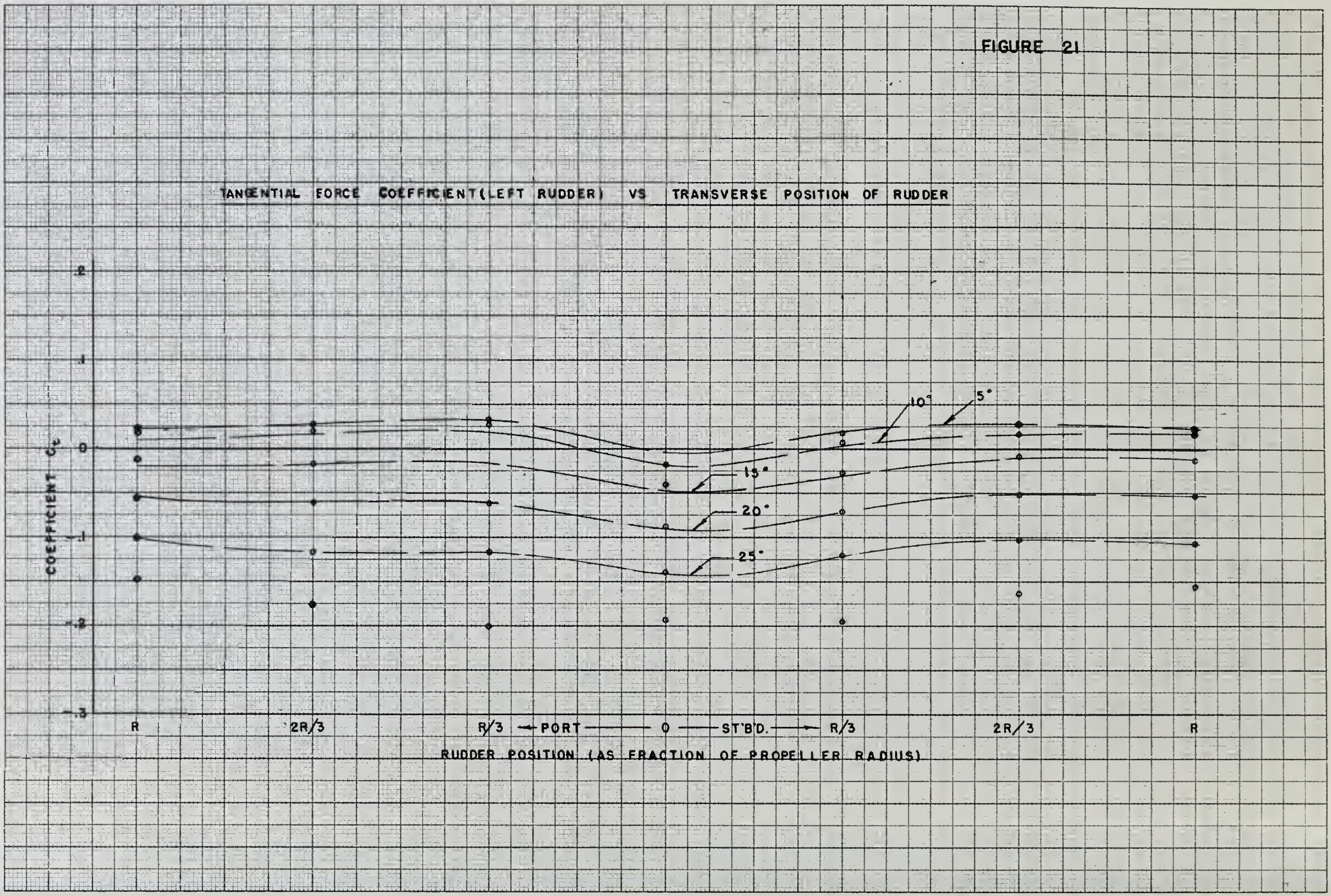
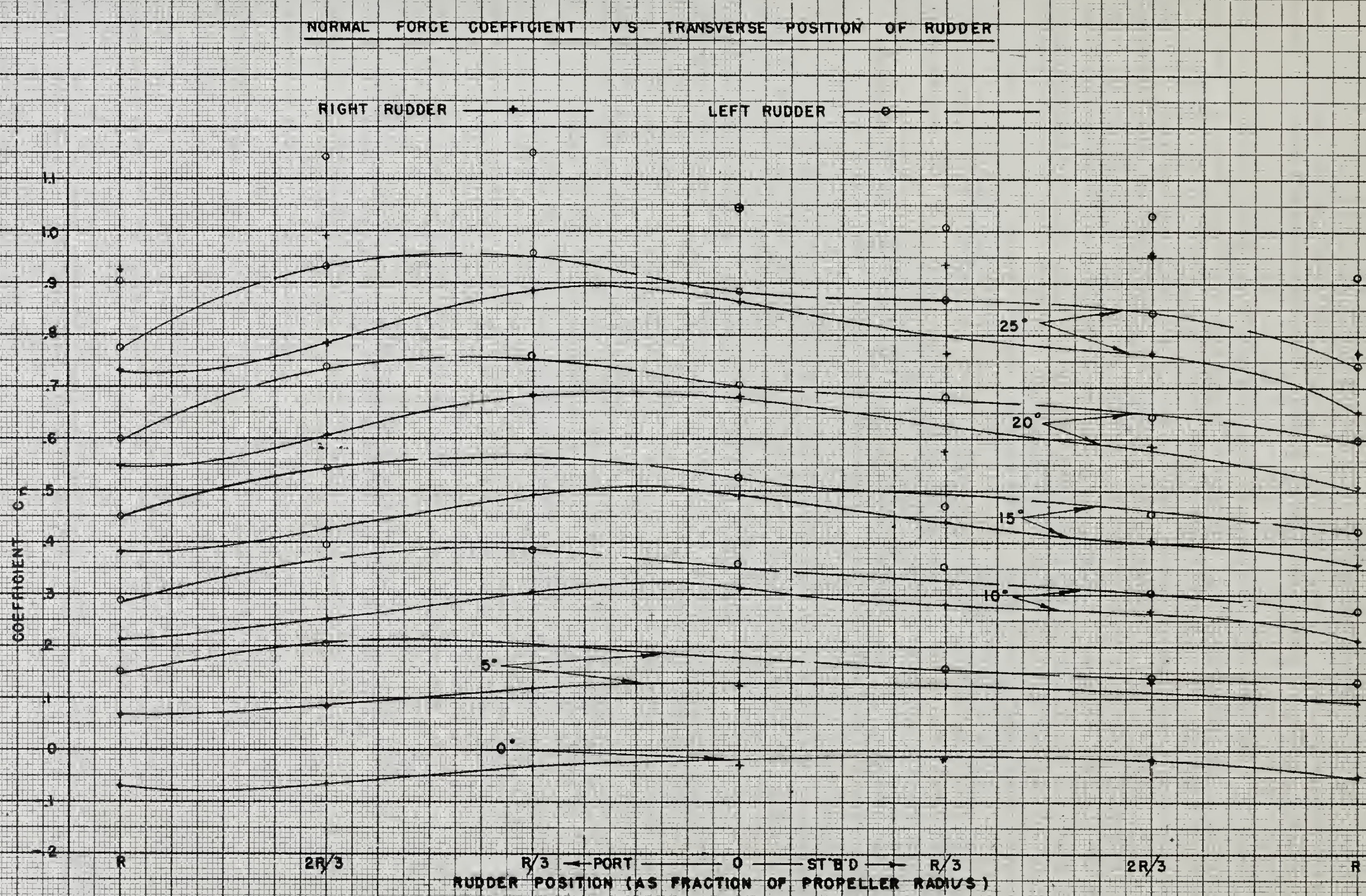


FIGURE 21



TANGENTIAL FORCE COEFFICIENT (LEFT RUDDER) VS TRANSVERSE POSITION OF RUDDER
COEFFICIENT C_t
.2
.1
0
-.1
-.2
-.3
10°
5°
15°
20°
25°
R
2R/3
R/3 ← PORT
0
ST'B'D. → R/3
2R/3
R
RUDDER POSITION (AS FRACTION OF PROPELLER RADIUS)

FIGURE 22



NORMAL FORCE COEFFICIENT VS TRANSVERSE POSITION OF RUDDER
RIGHT RUDDER
LEFT RUDDER
COEFFICIENT C_n
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
25°
20°
15°
10°
5°
0°
R
2R/3
R/3 ← PORT — 0 — ST'B'D → R/3
2R/3
R
RUDDER POSITION (AS FRACTION OF PROPELLER RADIUS)

V. DISCUSSION OF RESULTS

From the individual curves of C_L and C_D versus angle of attack, Figures 4 to 17, it appears that the values of the coefficients at the various angles of attack are in the right order of magnitude as compared with values obtained from previous investigations for a similar rudder in a free stream[4]. Further the general characteristics of the curves appear to be reasonable by the same standard. There is apparently some tendency towards higher coefficients when the rudder is in certain positions over corresponding free stream values. A direct comparison may be obtained by comparing these curves with those of Gogen and Tara[5]. It should be noted, however, that the investigation of the latter thesis was conducted with the tunnel operating in its designed direction. For this reason it is probable that flow conditions varied between the two theses, and direct comparisons might be misleading. The intent of the present investigation, as stated previously, has been limited deliberately to comparisons of relative characteristics among the various transverse positions, and assuming that angle of attack and rudder angle are the same. It is recommended that a spherical or universal pitot tube be used in future investigations in order to obtain three components of velocity. This would eliminate the necessity for the assumption concerning angle of attack.

In evaluating the results of this thesis, all information must be examined in the light of the fact that a right-hand propeller was used, and that the same information for a left-hand

propeller must be worked to the opposite hand. A right-hand propeller is defined as one turning clockwise when viewed from astern.

From the plot of lift coefficient versus transverse rudder position as a fraction of the propeller radius, Figure 18, it is immediately apparent that the lift coefficient falls off sharply for both left and right rudder for all rudder positions on the starboard side of the propeller axis. Similarly it is apparent that for rudder positions further outboard than two thirds of the propeller radius on the port side of the axis the lift coefficient decreased rapidly. The optimum position for maximum C_L, therefore, narrows to the range between the propeller axis and two thirds of the radius to port. Further it is apparent as the rudder position is varied from one third to two thirds of the radius to port, that while C_L for left rudder is higher than that for the centerline position, C_L for right rudder is dropping sharply. Since it is patent that a ship which will turn well in one direction only is undesirable, the optimum range is further narrowed to the range between the propeller axis and one third of the radius to port. Within this range therefore a close scrutiny of results is required.

For left rudder within this range the rudder position at one third of the radius to port is quite obviously the position of maximum C_L for all rudder angles. For right rudder, maximum values of C_L occur progressively closer to the propeller axis as the angle of attack decreases, with the best value appearing at about one fourth of the radius to port for an angle

of attack of 25°. Taking right and left rudder together to obtain an optimum value of C_L for the combination, it would appear that so far as C_L alone is concerned the best rudder position would be between one sixth to one third of the radius to port depending upon the particular rudder angle for which optimum turning characteristics are desired. It will be noted that the points for an angle of attack for 30° are plotted but are not cross faired. These curves were omitted deliberately since it was found that rudder breakdown was beginning at or near the 30° positions and any curves plotted through these points could only be misleading. This applies to all of the cross curves of coefficient versus transverse position.

From the plot of drag coefficient versus transverse rudder position, Figure 19, a clearly defined minimum value of C_D is seen for all left rudder angles at about one sixth of the propeller radius to starboard. Further, the value of C_D for all left rudder angles is seen to have two maximum values, the greater of which occurs at a rudder position of approximately one half the propeller radius on the port side, and the lesser at a rudder position of approximately one half the radius on the starboard side. As the rudder moves outboard of either of these two positions of maximum value, the coefficient decreases with increasing distance from the centerline.

For right rudder values of C_D, a minimum value is apparent for all rudder angles at about five sixths of the propeller radius on the port side, and a maximum value is noted at rudder positions varying from about one sixth of the radius on

the port side to about one half the radius on the port side.

Considering right and left rudder together to obtain an optimum value of C_D for the combination, there is a minimum value at approximately one-sixth radius on the starboard side and low values at both extremes of the propeller race. In view of the preceding analysis of C_L, it would appear that the position for minimum C_D nearest the centerline is of the most interest.

The curves of C_N and C_T, Figures 20, 21, and 22, show the same trends as those of C_L and C_D as would be expected. They are included since these coefficients are not infrequently used.

The results would appear to indicate that the optimum location for a rudder behind a right-hand propeller may not be on the conventional centerline position but possibly at a location near one sixth of the propeller radius to starboard. Further intensive investigation would, of course, be required to confirm this observation. It is recommended that future investigations be along the lines indicated below:

1. A further investigation of lift and drag, employing smaller increments of transverse position, in the range from one-third radius port to one-third radius starboard.
2. A further investigation employing various combinations of tunnel and propeller speeds.
3. A further investigation employing various combinations of rudders and propellers.

4. A complete investigation of flow conditions across the propeller race using a spherical or universal pitot tube. This would eliminate the necessity for assuming that angle of attack equals rudder angle.

VI. CONCLUSIONS

For a rudder of the type used in these experiments, operating behind a right-hand propeller the following conclusions may be stated:

A. Lift Coefficient

1. For right rudder, rudder position for maximum C_L varies from one third of the propeller radius to the port side of the propeller centerline at an angle of attack of 25° to one third of the radius on the starboard side for an angle of 0°. A reasonable mean position for optimum C_L at all angles of attack could be taken at the centerline.

2. For left rudder, maximum C_L for all angles of attack occurs at a rudder position approximately one third of the propeller radius to the port side of the propeller centerline.

3. An average of right and left rudder values for optimum C_L indicates that this will occur at a rudder position between one sixth and one third of the propeller radius to the port side of the propeller centerline.

B. Drag Coefficient

1. For right rudder, the rudder position for minimum C_D occurs at about five sixths of the propeller radius to the port side of the propeller centerline. A position of high C_D occurs between

one sixth and one half of the propeller radius on the port side.

2. For left rudder, a rudder position of approximately one sixth of the propeller radius on the starboard side of the propeller centerline gives minimum C_D. Maximum values of C_D occur at about one half of the propeller radius on both sides of the centerline and decrease with further movement towards both extremes of the race.

C. <u>Optimum Rudder Location</u>

On the basis of this investigation alone, using a single right-hand turning propeller, a single rudder and constant speed, there is evidence to indicate that an optimum rudder location, not necessarily on the centerline, does exist where high lift-drag ratio and high C_L occur simultaneously.

VII. RECOMMENDATIONS

It is recommended that future investigations be along the lines indicated below:

1. A further investigation of lift and drag, employing smaller increments of transverse position, in the range from one-third port to one-third starboard.

2. A further investigation employing various combinations of tunnel and propeller speeds.

3. A further investigation employing various combinations of rudders and propellers.

4. A complete investigation of flow conditions across the propeller race using a spherical or universal pitot tube. This would eliminate the necessity for assuming that angle of attack equals rudder angle.

VIII. APPENDIX

A. Supplementary Introduction

Certain phases of the investigation not included in the main body of the report are presented here for the benefit of those interested in the technical aspects of the problem so that the methods used and results obtained may be independently evaluated.

B. Details of Procedure

1. Propeller speed - The propeller revolutions were determined by an electric clock counter mechanism which automatically counts the revolutions over intervals of one tenth of a minute .

2. Tunnel speed - For the purpose of setting tunnel speed, a magneto was attached to the tunnel impeller shaft and the voltage generated was read on a copper oxide rectifier type voltmeter. This arrangement was used for the coarse adjustment; the fine velocity reading being given by the fixed pitot tube described in the body of this report.

3. Modification to propeller tunnel - Reversing the flow in the tunnel was accomplished by a switching arrangement which reversed the polarity of the impeller motor. It was necessary, however, to provide an additional thrust bearing on the impeller shaft, since the existing bearing was capable of resisting thrust in the ahead direction only.

4. Dynamometer calibration curves - It should be noted that the calibration curves shown in Figure 23 are not considered reliable for the upper transverse, upper longitudinal, and torque gauges. During the calibrations it was found that the curves for the lower transverse and lower longitudinal gauges could be repeated at will, but that the curves for the upper gauges were somewhat erratic, while those for the torque gauges seemed to depend solely upon the tension in the machine screws which secured the linkages to the strain gauge itself. Since the tension in these screws varied widely from one calibration run to another (although it could be held constant during any single run) and further since during the test runs the tension in these screws changed due to the vibration in the dynamometer, the use of the torque gauge was abandoned. On the other hand, both calibration and test readings could be repeated easily for the two lower gauges and this thesis relies upon the readings of these two gauges.

C. Tables of data and calculated coefficients - TABLES I through XIV.

Original data is shown in the tables included in the following pages under the columns marked LOWER LONGITUDINAL GAUGE READING and LOWER TRANSVERSE GAUGE READING.

TABLE OF DATA AND CALCULATED COEFFICIENTS

RIGHT RUDDER

RUDDER POSITION: 3" TO PORT OF CENTERLINE

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5835
LOWER TRANSVERSE 6005

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. -FORCE COEF.
0	5730	5875	-.0662	.0604	-.0661	.0604
5	5740	6130	.0644	.0546	.0698	.0487
10	5705	6400	.2060	.0761	.2155	.0390
15	5625	6710	.3675	.1231	.387	.0239
20	5530	7000	.519	.1786	.549	-.0095
25	5400	7320	.686	.2550	.731	-.0590
30	5230	7660	.864	.3540	.926	-.1239
35	5050	7890	.984	.4600	1.070	-.1880

TEMPERATURE °F 48

$\rho/2 \, AV_0^2 = 11.555$

TABLE OF DATA AND CALCULATED COEFFICIENTS

LEFT RUDDER

RUDDER POSITION: 3" TO PORT OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 5970

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	---	---	---	---	---	---
5	5750	5680	.1472	.0344	.1499	.0214
10	5690	5420	.2793	.0690	.2864	.0193
15	5630	5110	.4365	.1032	.4489	-.0133
20	5545	4825	.5910	.1521	.5985	-.0557
25	5400	4510	.7435	.2355	.7745	-.1008
30	5245	4240	.8580	.3242	.9050	-.1481

TEMPERATURE °F 61

$\rho/2 \, AV_0^2 = 11.544$

TABLE OF DATA AND CALCULATED COEFFICIENTS

RIGHT RUDDER

RUDDER POSITION: 2" TO PORT OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL	5835
LOWER TRANSVERSE	6005

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	5730	5880	-.0636	.0604	-.0636	.0604
5	5720	6155	.0781	.0662	.0836	.0591
10	5695	6470	.2425	.0806	.252	.0415
15	5620	6790	.409	.1240	.427	.0028
20	5520	7120	.582	.1815	.609	-.0286
25	5410	7450	.755	.2445	.786	-.0970
30	5190	7780	.928	.3720	.991	-.1411
35	5010	8100	1.093	.4750	1.066	-.2370

TEMPERATURE °F 47

$\rho/2 \, A V_0^2 = 11.555$

TABLE OF DATA AND CALCULATED COEFFICIENTS

LEFT RUDDER

RUDDER POSITION: 2" TO PORT OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 5970

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF,	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	---	---	---	---	---	---
5	5725	5570	.2038	.0489	.2065	.0266
10	5655	5205	.3890	.0890	.3980	.0199
15	5595	4930	.5295	.1233	.5430	-.0175
20	5470	4565	.7150	.1954	.7375	-.0609
25	5310	4220	.8905	.2869	.9300	-.1168
30	5080	3850	.9345	.4195	1.1420	-.1769

TEMPERATURE °F 60

$\rho/2\, A V_0^2 = 11.546$

TABLE OF DATA AND CALCULATED COEFFICIENTS

RIGHT RUDDER

RUDDER POSITION: 1" TO PORT OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5835
LOWER TRANSVERSE 6005

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	5720	5950	-.0281	.0660	-.0281	.0661
5	5710	6240	.1226	.0719	.1286	.0609
10	5670	6570	.295	.0950	.3065	.0422
15	5590	6915	.475	.1410	.495	.0135
20	5460	7250	.649	.216	.685	-.0193
25	5320	7620	.843	.296	.764	-.0876
30	5100	8000	1.041	.423	.889	-.1548
35	4910	8300	1.199	.532	.985	-.2555

TEMPERATURE °F 46

$\rho/2\, A V_0^2 = 11.555$

TABLE OF DATA AND CALCULATED COEFFICIENTS

LEFT RUDDER

RUDDER POSITION: 1" TO PORT OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 5970

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	--	--	--	--	--	--
5	5720	5560	.2085	.0517	.2120	.0334
10	5650	5230	.3763	.0919	.3863	.0253
15	---	---	---	---	---	---
20	5460	4530	.733	.2009	.758	-.0614
25	5290	4170	.9166	.2992	.9568	-.1164
30	5100	3820	1.0945	.4005	1.1484	-.2004

TEMPERATURE ^{o}F 59.5

$\rho/2\, AV_o^2 = 11546$

TABLE OF DATA AND CALCULATED COEFFICIENTS

RIGHT RUDDER

RUDDER POSITION: ON CENTERLINE OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5835
LOWER TRANSVERSE 6005

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	5790	5950	-.0280	.0259	-.0280	.0259
5	5765	6245	.1251	.0402	.1285	.0292
10	5710	6600	.3105	.0737	.3180	.0186
15	5630	6920	.4780	.1180	.4920	-.0098
20	5530	7270	.6600	.1842	.6820	-.0525
25	5380	7610	.8370	.2620	.8650	-.1165
30	5180	7900	.9880	.3770	1.043	-.1675
35	4990	5030	1.147	.4860	1.217	-.2585

TEMPERATURE $^{\circ}F$ 44

$\rho/2 \; AV_o^2 = 11.556$

TABLE OF DATA AND CALCULATED COEFFICIENTS

LEFT RUDDER

RUDDER POSITION: ON CENTERLINE OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 5970

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	---	---	---	---	---	---
5	---	---	---	---	---	---
10	5730	5250	.3582	.0459	.3609	-.0170
15	5640	4950	.5195	.0978	.5275	-.0403
20	5535	4610	.6908	.1579	.7028	-.0878
25	5380	4280	.8609	.2474	.8858	-.1395
30	5190	4005	1.0018	.3559	1.0439	-.1929

TEMPERATURE °F 58.5

$AV_0^2 = 11.547$

TABLE OF DATA AND CALCULATED COEFFICIENTS

RIGHT RUDDER

RUDDER POSITION: 1" TO STARBOARD OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 6010

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	5760	5975	-.0178	.0287	-.0178	.0287
5	5750	6250	.1251	.0345	.1278	.0235
10	5725	6535	.2735	.0489	.2777	.0005
15	5675	6845	.4356	.0778	.4412	-.0372
20	5500	7060	.5480	.1782	.5753	-.0190
25	5400	7400	.7254	.2357	.7656	-.0943
30	5200	7700	.8815	13504	.9386	-.1378

TEMPERATURE ^{o}F 54

$\rho/2 \, AV_o^2 = 11.550$

TABLE OF DATA AND CALCULATED COEFFICIENTS

LEFT RUDDER

RUDDER POSITION: 1" TO STARBOARD OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 5970

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF	TANGENT. FORCE COEF.
0	---	---	---	---	---	---
5	5755	5660	.1575	.0317	.1596	.0177
10	5690	5290	.3458	.0690	.3525	.0079
15	5640	5050	.4665	.0976	.4685	-.0268
20	5520	4665	.6630	.1665	.6880	-.0706
25	5360	4320	.8398	.2582	.8700	-.1202
30	5160	3930	1.0380	.3730	1.085	-.1959

TEMPERATURE °F 62

$\frac{\rho}{2} A V_0^2 = 11.543$

TABLE OF DATA AND CALCULATED COEFFICIENTS

RIGHT RUDDER

RUDDER POSITION: 2" TO STARBOARD OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 6010

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	5770	5980	-.0155	.0230	-.0155	.0230
5	5780	6260	.1302	.0172	.1315	.0058
10	5730	6520	.2658	.0459	.2690	-.0010
15	5670	6780	.4010	.0805	.4083	-.0260
20	5550	7100	.5684	.1495	.5839	-.0545
25	5445	7450	.7513	.2094	.7683	-.1272
30	5280	7780	.9222	.3045	.9525	-.1972

TEMPERATURE $^\circ$F 56

$\rho/2\ AV_0^2 = 11.549$

TABLE OF DATA AND CALCULATED COEFFICIENTS

LEFT RUDDER

RUDDER POSITION: 2" TO STARBOARD OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 5970

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF	DRAG COEF.	NORMAL FORCE COEF	TANGENT. FORCE COEF.
0	---	---	---	---	---	---
5	5740	5700	.1371	.0402	.1401	.0283
10	5690	5390	.2945	.0690	.3022	.0167
15	5630	5100	.4415	.1091	.4555	-.0089
20	5510	4745	.6235	.1723	.6450	-.0513
25	5360	4380	.8098	.2640	.8450	-.1027
30	5160	4055	.9740	.3670	1.0300	-.1641

TEMPERATURE ^{o}F 62

$\rho/2\, AV_o^2 = 11.543$

TABLE OF DATA AND CALCULATED COEFFICIENTS

RIGHT RUDDER

RUDDER POSITION: 3" TO STARBOARD OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 6010

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF.	TANGENT. FORCE COEF.
0	5770	5920	-.0458	.0230	-.0458	.0230
5	5765	6180	.0884	.0259	.0908	.0181
10	5745	6420	.2132	.0374	.2163	-.0002
15	5690	6690	.3543	.0690	.360	-.0251
20	5600	6970	.5000	.1208	.5104	-.0578
25	5480	7225	.6328	.1896	.6540	-.0951
30	5310	7390	.7189	.2872	.7665	-.1099

TEMPERATURE $^{\circ}$F 57

$\rho/2 \, AV_0^2 = 11.548$

TABLE OF DATA AND CALCULATED COEFFICIENTS

LEFT RUDDER

RUDDER POSITION: 3" TO STARBOARD OF PROPELLER SHAFT

ZERO GAUGE READINGS:

LOWER LONGITUDINAL 5810
LOWER TRANSVERSE 5970

ANGLE OF ATTACK	LOWER LONG'L GAUGE READING	LOWER TRANSVERSE GAUGE READING	LIFT COEF.	DRAG COEF.	NORMAL FORCE COEF	TANGENT. FORCE COEF.
0	---	---	---	---	---	---
5	5750	5715	.1298	.0345	.1320	.0230
10	5700	5440	.2697	.0632	.2682	.0154
15	5640	5150	.4160	.0891	.4270	-.0152
20	5540	4830	.5800	.1551	.5985	-.0530
25	5430	4555	.7200	.2180	.7450	-.1068
30	5250	4260	.8695	.3219	.9145	-.1561

TEMPERATURE ^{o}F 62

$\rho/2 \; AV_o^2 = 11.543$

VIII. APPENDIX (Continued)

D. Sample Calculations

Coefficient calculations — Refer to Table III

Data:

Transverse position	2 inches port
Propeller speed	1500 R.P.M.
Average speed of race at rudder (V_o)	11.94 ft./sec. (from Fig. 3)
Rudder angle	20° right
Water temperature	47°F.
Rudder area	.0836 sq. ft.
LL (Lower longitudinal)	5620 micro units
LT (Lower transverse)	6790 micro units
Mass density of water (ρ)	1.9398 lb. sec.^{2}/ft.^{4}

	LL	LT
Dynamometer - zero reading	5835 mu	6005 mu
Dynamometer - 20° right rudder reading	5520 mu	7120 mu
Difference	315 mu (decreasing)	1115 mu (increasing)
Slope of calibration curve	150.5 mu/lb.	166 mu/lb.

$$\text{Drag} = \frac{315 \text{ mu}}{150.5 \text{ mu/lb.}} = 2.095 \text{ lbs.}$$

$$\text{Lift} = \frac{1115 \text{ mu}}{166 \text{ mu/lb.}} = 6.620 \text{ lbs.}$$

$\sin 20^\circ$	= .3420	$\cos 20^\circ$	= .9397
Drag x $\sin 20^\circ$	= .716 lbs.	Drag x $\cos 20^\circ$	= 1.965 lbs.
Lift x $\sin 20^\circ$	= 2.295 lbs.	Lift x $\cos 20^\circ$	= 6.31 lbs.

$$F_N = \text{Lift} \cos\theta + \text{Drag} \sin\theta = 6.31 \text{ lbs.} + .716 \text{ lbs.} = 7.03 \text{ lbs.}$$

$$F_T = \text{Drag} \cos\theta - \text{Lift} \sin\theta = 1.965 \text{ lbs.} - 2.295 \text{ lbs.} = -.330 \text{ lbs.}$$

$$k = \frac{\rho A V_o^2}{2} = \frac{1.9398 \times .0836 \times (11.94)^2}{2} = 11.55 \text{ lbs.}$$

$$C_L = \frac{\text{Lift}}{k} = \frac{6.72}{11.55} = .582$$

$$C_D = \frac{\text{Drag}}{k} = \frac{2.095}{11.55} = .1815$$

$$C_N = \frac{F_N}{k} = \frac{7.03}{11.55} = .609$$

$$C_T = \frac{F_T}{k} = \frac{-.303}{11.55} = -.0286$$

Slip calculation

Propeller	R.P.M.	=	1500
	R.P.S.	=	25
Rudder	d	=	.5 ft.
	p/d	=	1.0
	p x n	=	25 x .5 = 12.5 ft./sec.
Tunnel	V	=	11.22 ft./sec.

$$\text{Slip} = \frac{12.50 - 11.22}{12.50} \times 100 \quad 10.24\%$$

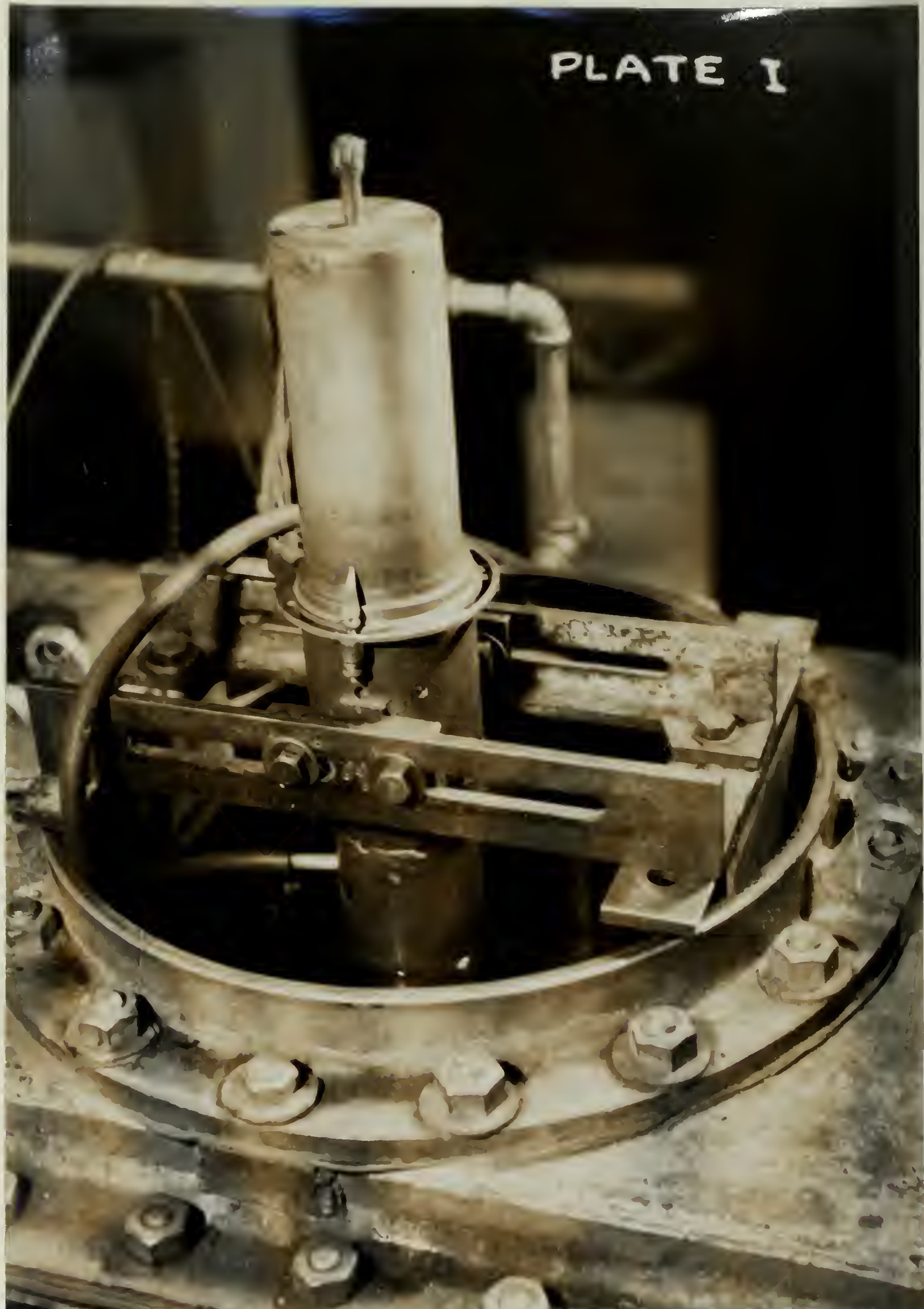


PLATE I


PLATE II
POSITION : ℄
α = 0°


PLATE III
POSITION: ℄
α = 30°


PLATE IV
POSITION: 2" ST'B'D α = 0°


PLATE V
POSITION: 2" ST'B'D
α: 30°

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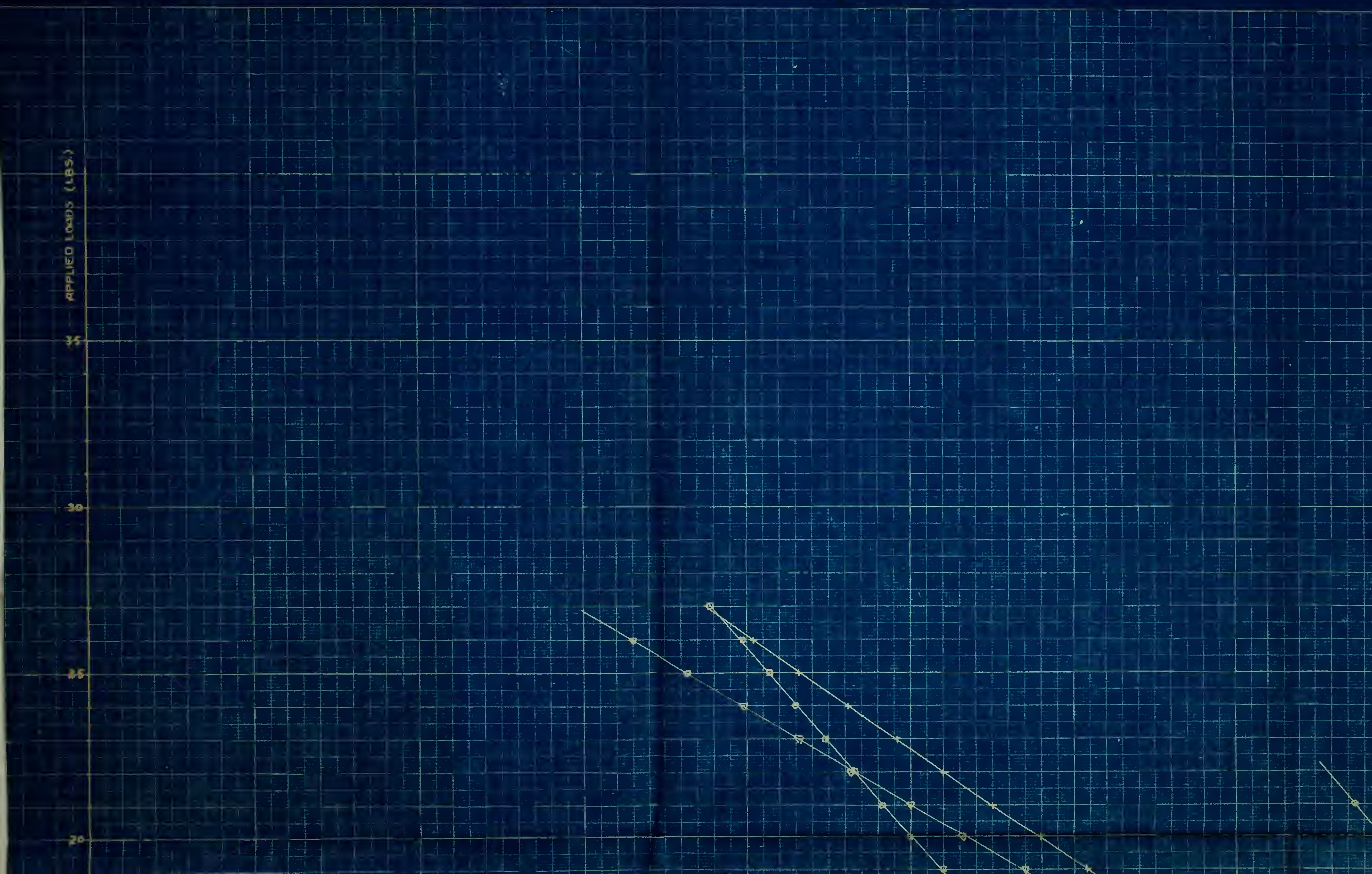
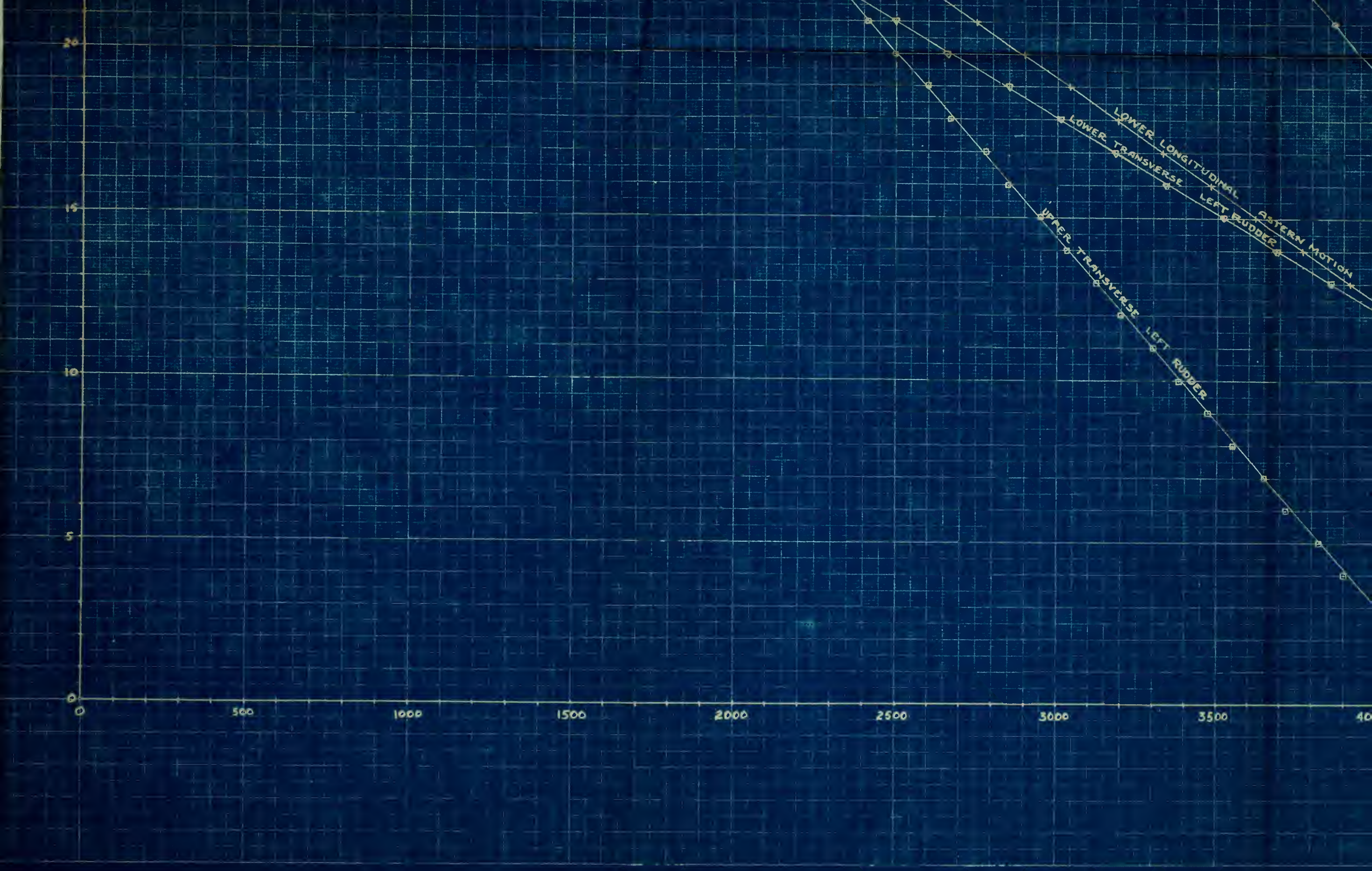
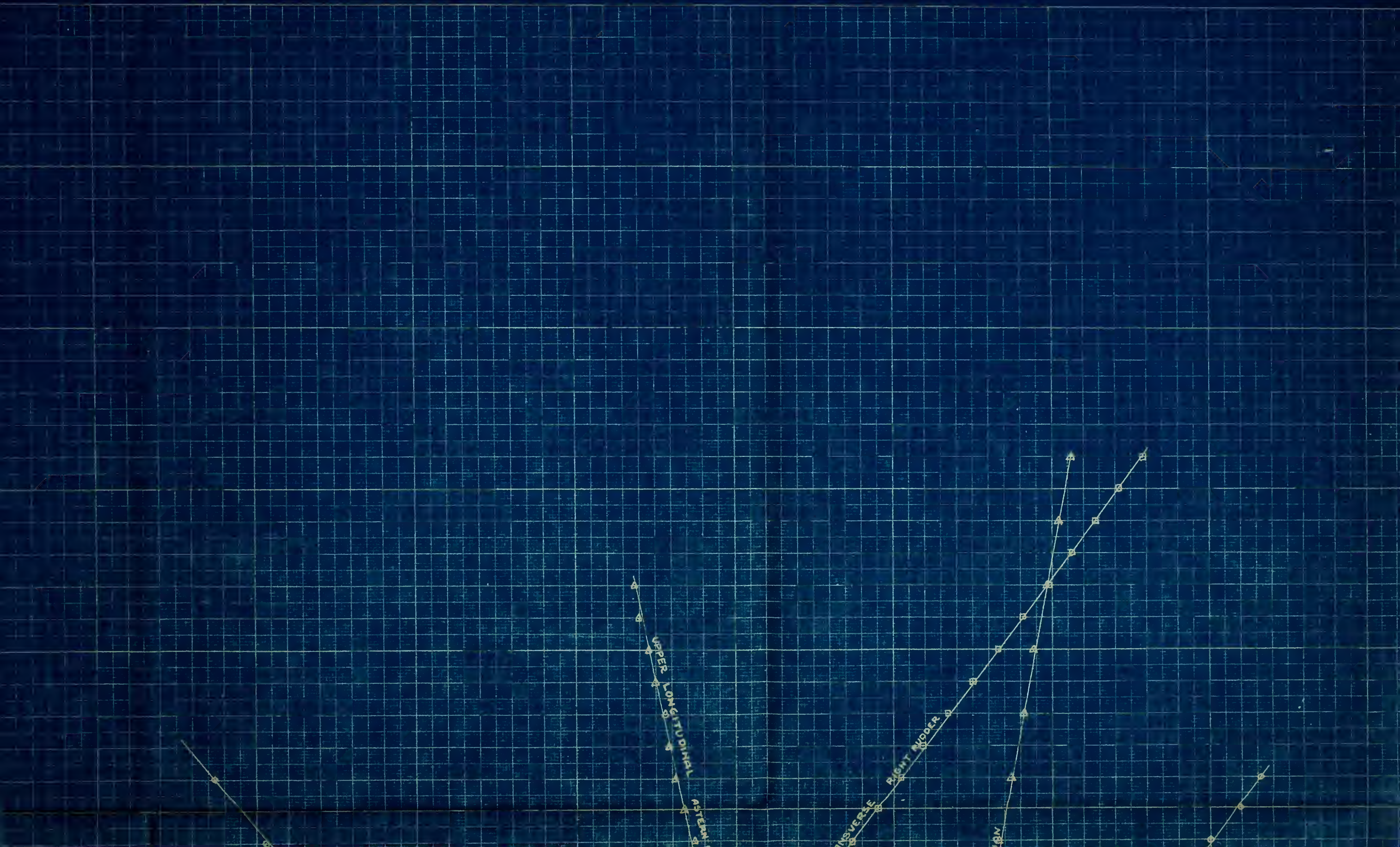
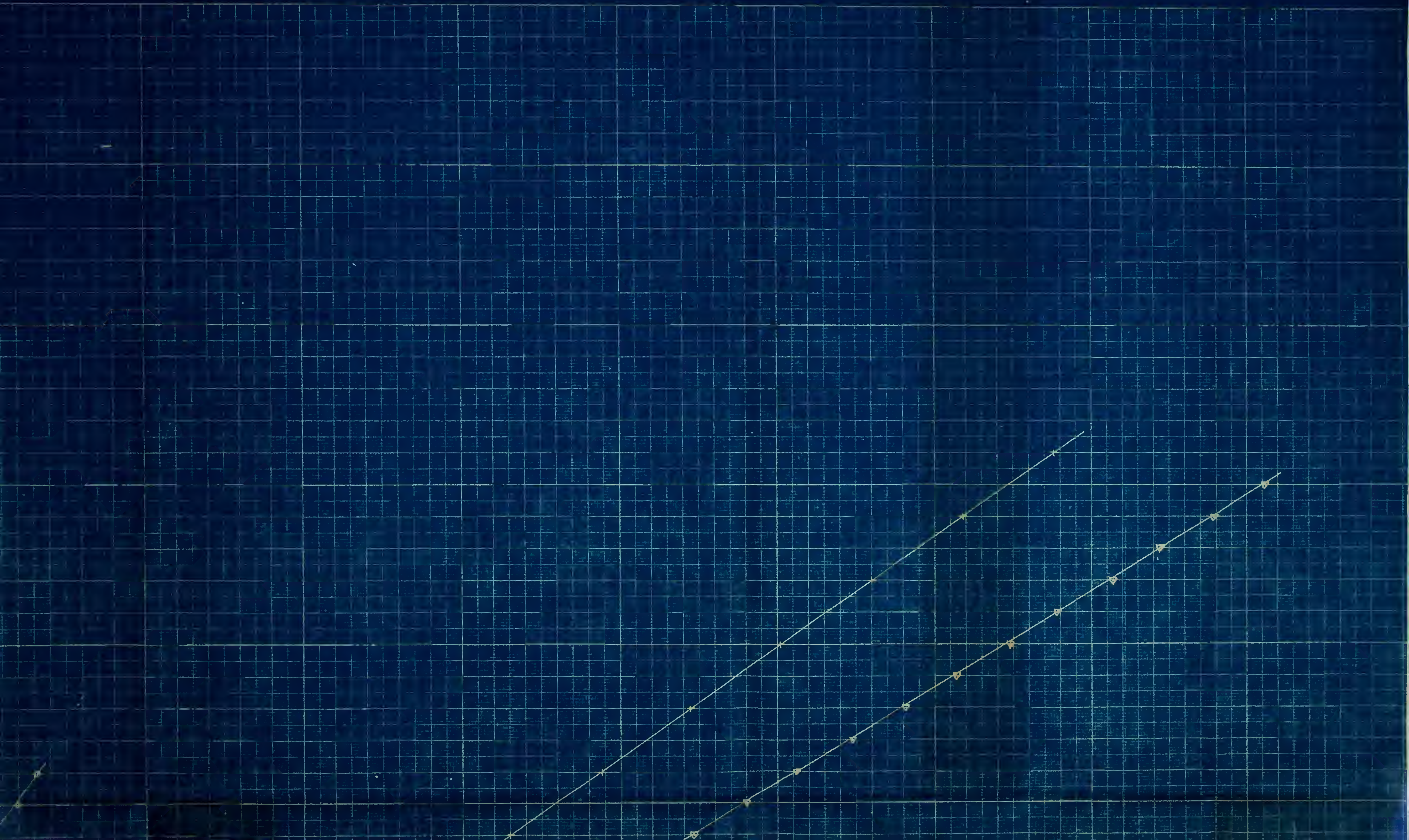

APPLIED LOADS (LBS.)
35
30
25
20



LOWER LONGITUDINAL ASTERN MOTION
LOWER TRANSVERSE LEFT RUDDER
UPPER TRANSVERSE LEFT RUDDER
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
3500


UPPER LONGITUDINAL
ASTERN
RIGHT RUDDER

LONGITUDINAL
LEFT RUDDER
ASTERN MOTION
TORQUE
LEFT RUDDER
ASTERN MOTION
UPPER TRANSVERSE
AHEAD MOTION
UPPER LONGITUDINAL
RIGHT RUDDER
TORQUE
RUDDER
LOWER
3500
4000
4500
5000
5500
6000
6500
7000
7500
INSTRUMENT READING



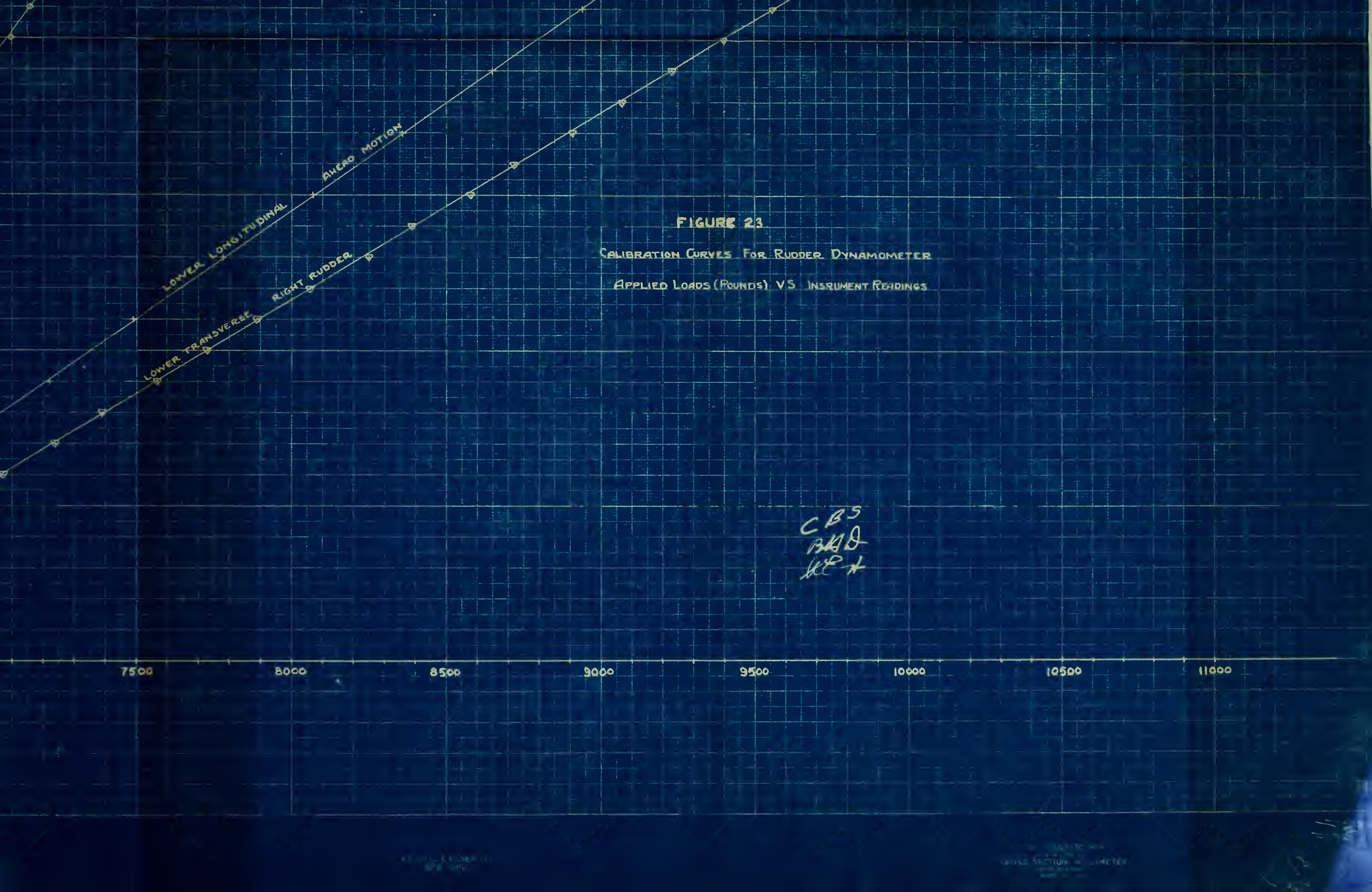


FIGURE 23

CALIBRATION CURVES FOR RUDDER DYNAMOMETER

APPLIED LOADS (POUNDS) VS INSRUMENT READINGS